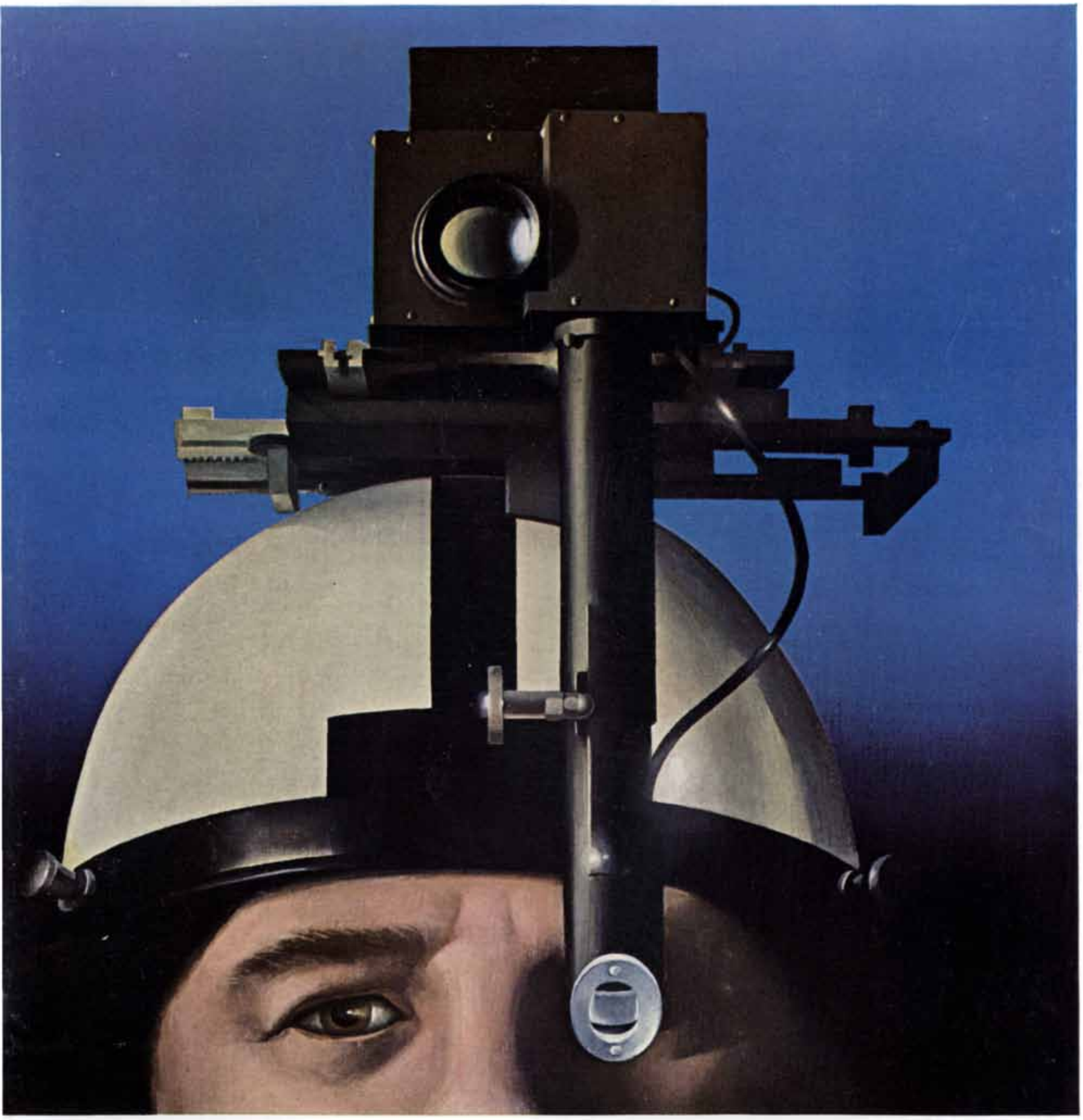
SCIENTIFIC AMERICAN



MOVEMENTS OF THE EYE

SEVENTY-FIVE CENTS

August 1968

We make it easier to fly.

We'll fly 23 million people this year. Our object is to make flying easier for every one of them.

1. We're making reservations even faster.
With the most sophisticated system in our industry.
It remembers the name, phone number and flight information on more than one million passengers.

2. We're eliminating the check-in line.
By taking your luggage and checking you aboard your flight at curbside.

3. We see that our jets are ready when you are.
By having skilled maintenance technicians who work through the night to have jets ready to fly in the morning.

4. We turn terminals into places to enjoy.
Visit any waiting area. You'll find comfortable seats in living-room-like settings.
Visit an Eastern Ionosphere Lounge. Here, first class passengers can enjoy the atmosphere of a private club.

5. We put you at ease in the air.
An Eastern stewardess knows more about making life easy for you than most people learn in a lifetime.

6. We make dining aloft a pleasure.
We're substituting our cooking for yours, so we try to offer something as good. We put fine restaurant cooking on selected Ionosphere flights, with an entree choice in both first class and coach.

7. We put a stopwatch on our baggage handlers.
If the clock shows too much time, we find the reason and correct it.

8. We have the finest jets.
With 166 now, and another 37 to be added this year. In the 1970's, the Lockheed 1011 and the supersonics will join this fleet. All piloted by seasoned professionals.

9. We have other people you'll never meet.
People who work out convenient schedules, vacation packages, low-priced fares and pay-as-you-go plans.
All with one goal in mind: to make flying easier for you.

EASTERN

The NCR Century Series of computers.

When you learn how advanced they are, you'll know why others are old-fashioned.

It's going to change all your old ideas about computer costs and capabilities.

The Century Series offers a price/performance ratio unequalled in the industry.

It's the first truly compatible family of computers that incorporates the most modern technological developments. It's perfect for all levels of users. For both business and scientific applications.

The Century Series will meet your requirements today and tomorrow. You can expand capacity and power as your needs change. Just plug in a more powerful processor. Same peripherals. And no re-programming. True upward compatibility.

Internal memories range from 16,384 to 524,288 bytes. Future Century computers will offer memories with up to one million bytes. On-line processing and three-way simultaneity offered in the lowest cost member. It rents for less than $2000 a month with an extended contract. You can move up to multi-programming and nine-way simultaneity. Eventually to multi-processing and 17-way simultaneity.

You get the benefit of great technological developments. Monolithic integrated circuitry is used throughout. With the power of conventional or hybrid circuits but at a fraction of the size. Thin film, short rod memories. With speed in the 800 nanosecond range, yet lower cost than core memories because of automated manufacturing techniques. (Only $375 for an additional 16,000 bytes of memory.)

A dual spindle disc unit that sets a new standard in the industry. With 45 ms average access time, it's the fastest removable disc unit in the industry. Each recording surface with 12 floating read/write heads.

Card Random Access Memory (CRAM) units each with on-line storage capacities over 125 million bytes. Magnetic tape drives with transfer rates up to 240 kc. Line printers with speeds up to 3000 LPM. A wide range of peripheral devices: punched card and tape input/output units, MICR sorter/readers, OCR scanners and remote on-line devices.

Sophisticated software! No other computer in the same price range as the Century computer can offer as much. Compilers, operating systems, applied programs and utility routines. All written, tested and ready-to-go. Programming languages: COBOL, FORTRAN and NCR's own NEAT/3.

There's much more to tell. Call your NCR representative today for the story of the Century. Or write to The National Cash Register Company, Dayton, Ohio 45409.

NCR

THE NATIONAL CASH REGISTER COMPANY, DAYTON, 45409 ®

Our laser raises resistors' resistance.

Actual Size

Zap! And another delicate, precision resistor is trimmed to exacting tolerance—right through its glass envelope.

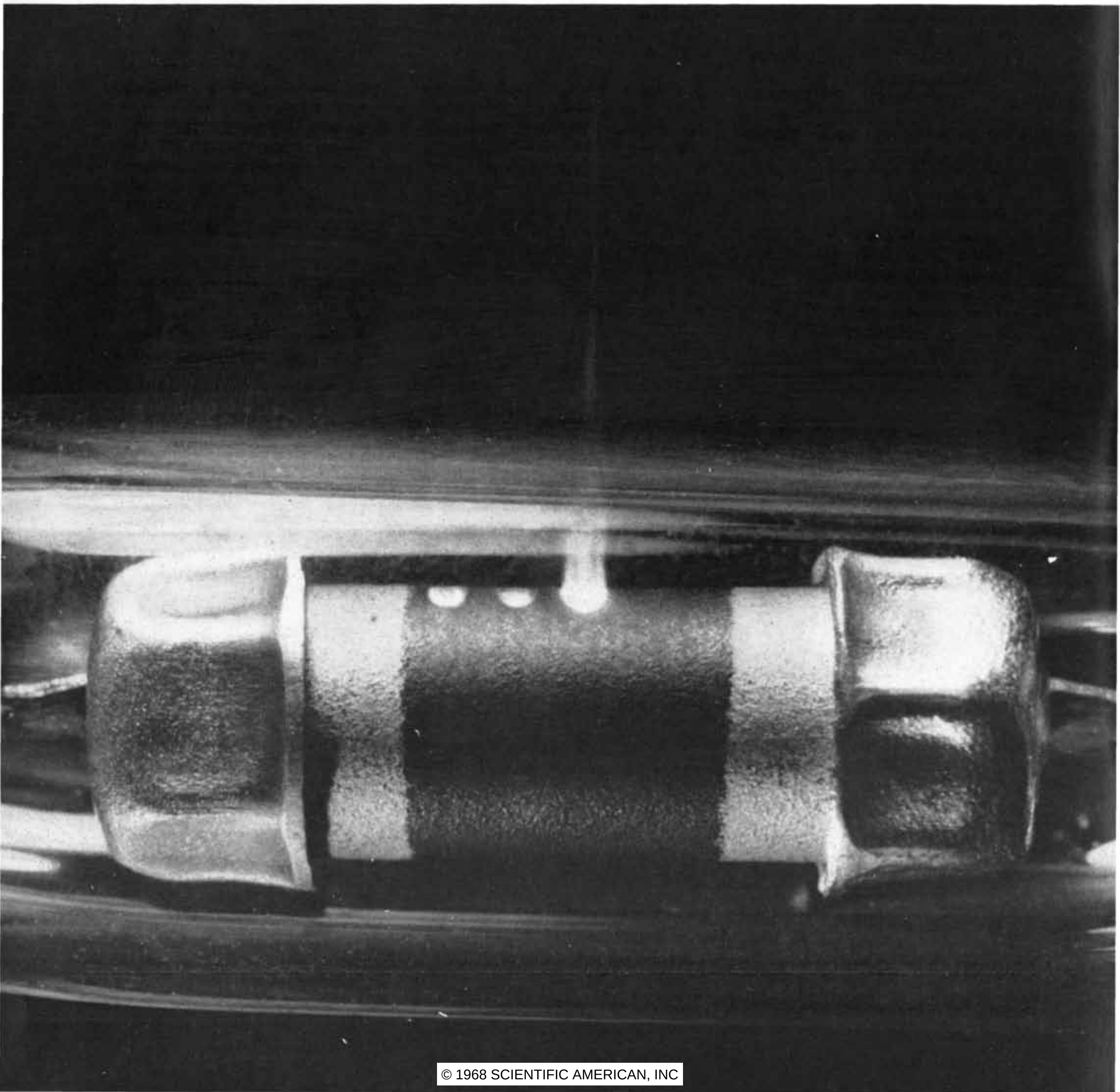
In times past we trimmed these resistors by mechanically removing deposited carbon from the ceramic cores—*before* we sealed them in an inert atmosphere. But the heat of sealing the glass capsules sometimes changed the resistors' value.

Now we're using a new method: Glass enclose the resistor first. Then direct carefully aimed q-switched laser beams through the glass. With about 20 to 40 billionths of a second pulses, some of the carbon is removed, in the form of spaced strips, increasing resistance until the exact value is reached.

Western Electric builds these devices to withstand trying conditions. Long-distance coaxial cables have them in repeaters every four miles. Without high reliability and stability, messages might be garbled by device variations caused by tropical humidity, desert heat or winter cold. So, we've had to develop some equally rigorous manufacturing techniques.

Not everything we make for the Bell System is required to battle the elements, but all must have the same kind of reliability. Because we're in the Bell System to help it serve you better.

Western Electric
MANUFACTURING & SUPPLY UNIT OF THE BELL SYSTEM



Established 1845 **SCIENTIFIC AMERICAN** August 1968 Volume 219 Number 2

ARTICLES

DEPARTMENTS

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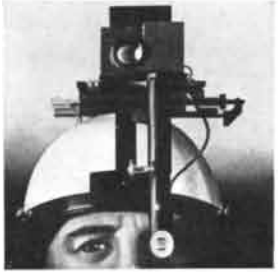

THE COVER

The painting on the cover shows a special camera designed by Norman H. Mackworth and E. Llewellyn Thomas for studying the movements of the eye (see "Movements of the Eye," by E. Llewellyn Thomas, page 88). The camera is mounted on a helmet that allows the subject to move his head during such visual activities as driving, flying and looking at pictures and other people. At the top is the main lens of the camera, which records on eight-millimeter motion-picture film the scene at which the subject is looking. Descending in front of the subject's left eye is a periscope on which is mounted a small light source that makes a bright highlight on the surface of the cornea; the periscope picks up the highlight and projects it onto the motion-picture film. The highlight is thus recorded on the film as a bright spot that shows where in the scene the subject was looking at each instant.

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LETTERS

Editor's note: The writer of the following letter is senior lecturer in economics at the Australian National University. In April and May of this year he traveled in six Chinese provinces as a guest of the Chinese Academy of Sciences, visiting 20 factories, six communes, docks, irrigation works, railroad switching yards and universities.

Sirs:

During my recent visit to China I found Genko Uchida's article "Technology in China" [Scientific American, November, 1966] a very valuable reference point for initiating discussion with Chinese factory personnel and industrial planners. A number of developments in China since his article appeared and additional Chinese comments on the issues he raises make further remarks on his article worthwhile.

With Uchida's overall impression that China will take 10 years to reach Japan's present level of industrialization I am in general agreement. He is also quite correct when he says that the manufacturing sector "lacks the base of feeder industries for making parts and components." The question is, though, why have the Chinese been content to follow a policy in which self-reliance, medium-scale technology and "making your own lathes" are pursued even at the cost of a lower productivity?

The answer is partly military and political. Provinces are being encouraged to become self-sufficient "base areas" in order to be able to meet any armed invasion. The policy of local self-reliance, of each factory making its own machine tools, is emerging even more strongly in the wake of the "cultural revolution." One reason is that it is easier for "reds" to manage self-reliant small enterprises; large, specialized factories by their nature depend on "experts," who may not be "red." Maoists are also said to approve of factory self-reliance as a way of cutting down on transport demands and because of their reluctance to build, at this stage of China's low "absorptive power" of capital, a network of feeder industries whose products would have to be rationed among jealous regional authorities.

The Chinese strategy is not completely without economic sense. Their attitude toward technique of production is that no equipment should be scrapped or technique be rejected so long as the materials used with them and the labor operating them cannot find a better use elsewhere. Many of the lathes built by the factories producing final goods were made out of scrap iron in the unpaid time of the workers. They are certainly less productive than the products of a specialized machine-building industry would be, but their social cost is very low. Again, the Chinese see some noneconomic benefits in people "relying on their own efforts." In the jargon of the academic economist, the social-welfare function is thereby enhanced.

Uchida says that without the specialized machine-building industries no circle of technical expertise will grow. This is true, and with heavy rates of investment elsewhere in the economy there is already a shortage of expertise. With a limited absorptive capacity for new fixed investment at the current Chinese level of economic development (due to the shortage of engineers and designers) some sectors must have priority and others must miss out. My guess is that lathes, fractional-horsepower motors and other inputs produced in the limited modern sector are now being absorbed by defense and agriculture. Later the industrial sectors may be able to receive more of them.

One advantage of the Chinese planning system is that it can have various levels of productivity within the same industry. Take textiles. In a private-enterprise economy the advent of a large modern mechanized mill will drive out the small-scale producer and earn huge profits for the modern plants, causing social dislocation and unemployment—particularly in Asia. In China the authorities can control price and investment in such a way as to prevent this, or they can allow both modern and small-scale indigenous producers to go ahead. Since profits are transferred to the state there is no automatic tendency for reinvestment followed by excess capacity and dismissals.

The disadvantage of the Chinese system is that with no free price mechanism there is no "discipline by the yuan," no check on managerial efficiency. That is why the "moral incentives" aspect has received so much emphasis during the cultural revolution. Instead of bribing managers to behave rationally (as in the Liberman scheme in the U.S.S.R.), the managers are put under pressure to have the "right" attitude toward society and are subjected to the discipline of the mass meeting.

I turn now to some specific points made by Uchida.

1. He says that "in the production of steel the Chinese mills are limited to the open-hearth-furnace technique without oxygen; they have not yet come to the liquid-oxygen converters." This is no longer so. Hardly was Uchida's article published when the Chinese opened their new pure-oxygen top-blown steel converter shop in Shanghai. This converter can produce more steel than 10 open-hearth furnaces of the same kind. In the new Shanghai shop loading, smelting and pouring are all automatically controlled. All the equipment was designed, built and installed by Chinese engineers and workers, and all the instruments, meters and electronic devices were made in China. The construction of the plant started in June, 1966, and was completed early in 1967.

2. Uchida believes a serious shortage of chemical fertilizer, which he measures as 12 pounds per acre (or a tenth of the amount used per acre in Japan), is holding back agricultural productivity, so that "it will take at least five to 10 years to raise [China's] agricultural productivity to a level at which it can provide her with sufficient capital for a major breakthrough in industrialization." Yet agricultural productivity has risen sharply in 1967 (by 10 percent), and the question of a shortage of chemical fertilizer cannot simply be judged by a comparison with Japan. Not only are conditions of soil fertility, rainfall and so on much different in Japan but also "fertilizer" assumes many forms. In most communes I was told that it was necessary to mix chemical fertilizer with organic fertilizer (pig manure particularly). There is, of course, a shortage. Production of chemical fertilizer was infinitesimal in 1949. By 1966 it had risen, as Uchida points out, to 7.5 million tons per year. But 20 plants under construction will come into operation during 1968 and 1969, raising output to 20 million tons as a contribution to the estimated need of 25 million tons. Moreover, in central and southern China a great deal of attention is being paid to the use of "green" manure, notably to the growing and "ploughing in" of hung hua ts'ao tzu (the species *Astragalus sinicus*, *Vicia cracca* or *Medicago hispida*), plants that transform phosphates into nitrogenous fertilizer at the rate of 500 kilograms of plant yielding 10 kilograms of fertilizer. This

is helping to ease shortages of the output of chemical plants.

3. Uchida made a well-deserved jibe at some Chinese automobiles, with sedans "as heavy as a small dump truck." The Chinese have evidently learned from this mistake: at the 1968 Spring Canton Fair they had on display four more pleasing models. One, similar to the Fiat, made in Shanghai weighs 560 kilograms and uses five liters of fuel per 100 kilometers. A second "Shanghai" sedan weighing 1.5 tons uses 9.6 liters per 100 kilometers. The largest, the "Honqui," an automatic-transmission six-seater, looked heavier, but not as heavy as a truck.

4. Uchida mentions the Chinese concentration on tractor production, "since labor-saving in farming is less urgent than increasing the productivity of the soil." This is true as a generalization, but it is not true of particular locations or particular periods in the rhythm of agriculture. Labor time saved during rice transplantation is very valuable in China, and it also is during harvest times. For that reason the Chinese are producing mechanical plows *cum* hoes, which they are selling for 200 yuan to the brigades, and also semimechanized rice transplanters selling for 90 yuan. The semimechanized rice transplanter can do four *mou* per day, compared with one *mou* done by a small team transplanting by hand, and the results in terms of quality of seedling planting are said to be good. At Leiyang in Hunan province they are producing a fully mechanized rice transplanter, but it is said to be difficult to maintain in working order.

5. Finally there is the question raised by Uchida of how near "the takeoff" into self-sustained growth the Chinese economy really is. Uchida says: "In 10 to 15 years she might attain a per capita income equal to Japan's present figure ($620). In that case China's gross national income would be about 70 percent as large as that of the U.S. How far off is the impending breakthrough for China?" Uchida concludes: "My own estimate is five to 10 years."

My own limited impressions and inquiries lead me to support Uchida on this point. It would be unwise, however, to be dogmatic. First, a series of excellent crops over five years could change the situation dramatically, releasing large resources for reinvestment in technological progress. Then there is the matter of the trend in investment and agricultural production. According to Alexander Eckstein's *Communist China's Economic Growth and Foreign Trade: Implications for U.S. Foreign Policy*, the Chinese economy grew at about 8 percent per annum during 1952–1959 and industrial production grew at 21 percent per annum. But the industrial share of the national product only began to equal the agricultural share in 1959. Since industrial production is now growing at least as fast as it was then, and its share of the national product is probably larger, whereas agricultural production since 1962 has been at least as high as it was in 1952–1959, the overall rate of growth is now at least 8 percent. A further supporting fact is that gross investment reached 27 percent of the gross national product for the first time in 1957, having risen from 19 percent in 1952. Now it must be running at about 27 percent of the gross national product, particularly in view of the fact that all China's international debt was liquidated by 1964. All of this suggests 10 years may be too long a "guesstimate" in establishing the timetable under which China will attain Japan's *current* level of economic development.

BRUCE MCFARLANE

School of General Studies
Australian National University
Canberra

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

AUGUST, 1918: "By way of commemorating the anniversary of Great Britain's entrance into the war, the British War Commission has made public some figures which show how great has been the contribution of the Empire to the Allied cause. The total enlistment throughout the Empire during the past four years has been 7,500,000 soldiers, and of these 60 per cent, or 4,500,000, were raised in England itself. In the four years of the war the British casualties have amounted to more than 2,500,000. Of these more than 500,000 have been killed, and at least an equal number so terribly wounded and broken that they will never be able to support themselves. Thus more than 1,000,000 British have been sacrificed in the four years of the war. Among these losses must be included practically all the officers and men of the small but highly efficient regular army that Great Britain threw into Flanders at the outset of the war to engage the right wing of the German army."

"English-speaking students of science may congratulate themselves on the opportunity afforded them by the recent publication in translation of *The Destinies of the Stars,* by the great Swedish chemist, astronomer and philosopher Svante Arrhenius. Although we have waited three years for this translation, we are compensated by the fact that it is extended to include astronomical discoveries down to 1917. It opens new vistas to the reader, particularly through planetary observations and a study of the relation of the stars to the Milky Way, and our surmises as to 'the changing fate and future position of the earth' are placed on surer foundations. Chapters on the climatic importance of water vapor and the atmosphere and physics of the stellar bodies lead naturally to a discussion of the chemistry of the atmosphere and the possible presence of life on worlds other than our own, and this theme is further developed in a lengthy chapter on Mars, a masterly review of observations and opinions. The sensationalist may not be over-pleased to reach the author's conclusion that we must 'consider Mars as unfit to harbor living beings,' but he may find comfort in the belief that Venus may become 'the dwelling place of the highest beings in our solar system.' "

"The longer the world war continues the greater becomes the conflict on the ground and in the air. In the latter sphere the activity has attained unbelievable proportions, as witness the recent British official statement reporting more than 120 German machines shot down in two days' fighting. The average wastage daily in aerial fighting is as great today as the wastage of a month in the early days of the war."

"Enthusiasts for prohibition, taking advantage of our disturbed conditions, insist on injecting their propaganda into public affairs, but even if they are successful in prohibiting the manufacture and sale of liquor, it will be a long time before laws alone will change long established habits, and we may fully expect that many people will undertake to make their own liquor. In some sections of the country this has been done for many years, in spite of strenuous efforts by the Government to root out the industry."

"Very gratifying to the nation at large is the whole-hearted way in which the colored people have responded to the call of war. The draft has been accepted with enthusiasm. An Army officer from the South tells us that the colored soldiers are proud of the uniform and the service. Moreover, in the work of preparation going on behind the fighting line the colored man is doing excellent service both in France and at home. After the war, when the question of extending the rights of the colored people comes up for discussion, their record during the war will be in evidence."

SCIENTIFIC AMERICAN

AUGUST, 1868: "A petition signed by 400 ladies has been presented to the Russian Minister of Public Instruction, praying that the Professors at the University might give special lectures for ladies so as to satisfy their legitimate desire for higher instruction."

"The *Revue Populaire* of Paris gives an account of some very curious experiments made by Dr. Claude Bernard. If oxygenized blood be injected into the arteries of the neck immediately after decapitation, warmth and sensibility return, the eye gets animated and displays such perception that an object shaken before it will cause winking of the eyelids and movements of eyeballs as though to avoid injury."

"A resident of Martigny, Switzerland, has lately organized a considerable trade in ice at Lausanne. The ice from the glaciers, having been sawed into regular cubes of small volume and perfect transparency, is placed in boxes and sent off by fast trains to various centers of population in France and arrives with very little waste."

"M. Lartet, at the last session of the Sociétés Savantes, presented an account of some human bones discovered by him in Dordogne. The age of these bones is judged to be equal to the mammoth, and they are considered to belong to the same geological period."

"From one of our German exchanges we copy a statement that a transparent metal has been discovered, the component parts of which are water-glass and copper: 'It is of a deep orange hue, can be melted and cast, wrought under the hammer and rolled. Files will not scratch it; it is translucent and capable of being wrought into ornaments of rare beauty.' This is evidently a chemical canard, unworthy of serious notice."

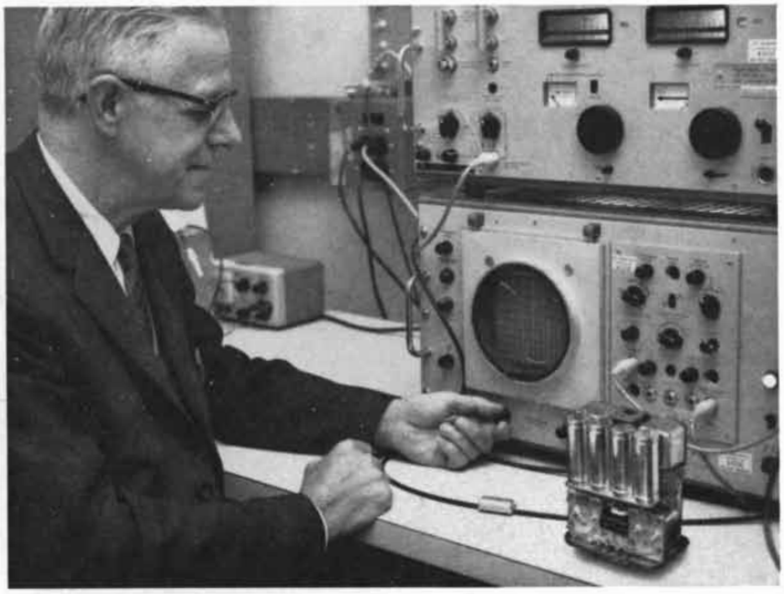
"In the southeast corner of the new territory of Wyoming is situated Cheyenne. This, the 'Magic City,' was laid out by General Dodge on the 20th and 21st of July, 1867. In one short year it has gained a resident population of more than 5,000, having once had perhaps as many gamblers, roughs and prostitutes. The citizens now are mostly of a very respectable class, though like all the Western towns it has a full quota of rumshops and their patrons."

"Since Milo of Crotona astonished the ancients by his six victories at the Olympic games, the world has been spasmodically given to getting on its muscle. We are now in the midst of one of these spasms. Base ball, rowing matches and feats of pedestrianism seem to rival in the public prints the attention which is claimed by political conventions, elections and scandal. We have a suspicion that many of those who engage in these matches, and who plead in their favor the old cant about the promotion of health and all the rest of it, will find in the end that in their particular case they have been otherwise than beneficial."

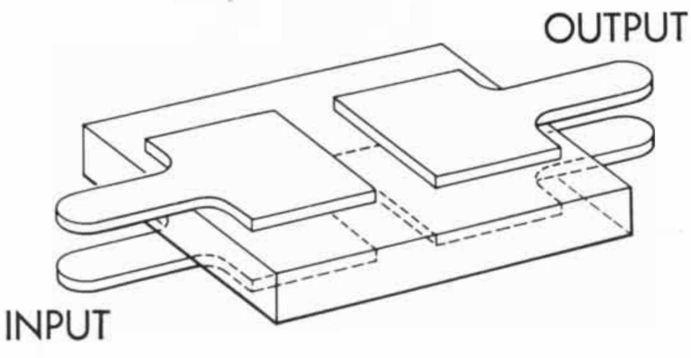
Report from

BELL LABORATORIES

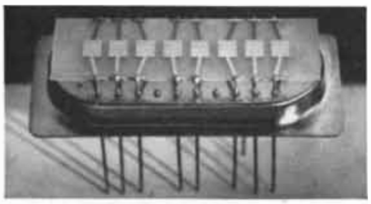
A Monolithic Filter



Roger A. Sykes, who directed the development program, checking the transmission characteristics of an eight-section 10-MHz monolithic filter (the tiny unit directly under the scope face). This unit replaces the larger filter seen to the right on the bench. Half-power points are 3.2 kHz apart.



Simple monolithic filter. Input and output resonators are formed by evaporating metal areas into opposite faces of a quartz plate. The resonators are coupled through the intervening quartz. Below, in actual size, is an eight-resonator monolithic quartz filter.



Electrical filters are widely used in communications systems to perform the important basic function of selecting, rejecting, and discriminating among various bands of frequencies.

Today's filters, depending on the design, might require a dozen or more components, including several quartz crystals. But now, as a result of work at the Allentown, Pa., location of Bell Telephone Laboratories, it is possible to design a quartz filter as a single, "monolithic" device.

The new filter is based on the fact that vibrational energy can be confined or "trapped" by pairs of metal-plated areas on opposite sides of a plate of crystalline quartz. The region within the crystal bounded by these areas thus becomes a localized resonator. A small amount of energy extends beyond this local region, however, and this energy can couple elastically to other resonators placed on the same piece of quartz. By choosing a suitable number of resonators and by spacing them properly, one can change the bandwidth of the filter and shape its in- and out-of-band characteristics.

The drawing (left) shows the simplest case—an input resonator and an output resonator coupled through the quartz plate. This would filter out all but a very narrow band of frequencies. The photograph (bottom) shows an eight-section filter designed to transmit a wider band of frequencies, with strong attenuation outside the band.

Monolithic filters are smaller and less expensive than earlier designs. Several types, in the 6-MHz to 20-MHz range, are now being produced for coaxial communications systems by the Western Electric Company in Merrimack Valley, Mass.

Bell Telephone Laboratories
Research and Development Unit of the Bell System


Can an electronic computer
DINER
Operators of fast-feed restaurants, as well as of many other commercial enterprises, can now enlist the aid of high-speed electronic computers to handle such continuing processes as order-taking, inventory and cash-flow control, record-keeping, and customer check and change computations. At the "nerve center" of each of these computers are miniature magnets called cores—used to store data in an information bank, or memory.
RCA knows how

run a business?

The astounding impact of the electronic computer on everyday life is brought about by its ability to retrieve and process stored information in as little as a few billionths of a second. While instructions on how to proceed and what to do are provided in its initial program, the information to be processed by the computer is constantly being written into, read out from, and rewritten into its depository of information, called the "memory".

Within a high-speed computer memory, information—in the form of magnetic currents—is stored in tiny doughnut-shaped devices called cores, which can be magnetized selectively into an "on" condition. This is represented digitally ("1" meaning "on", "0" meaning

Fig. 1

"off"). Sequences of such binary digits, referred to as "bits", are coded to denote symbols, letters or numerals. A fixed number of these symbols, called "words", is handled by most computers through the use of a random-access memory which stores and furnishes on demand words made up of multiple bits.

Each bit of information, in the form of "1" or "0", is stored in its own core—a ring of ceramic-hard magnetically-conductive ferrite material. These cores are grouped together in an array and strung with a network of hair-fine wires that conduct electric currents to energize them. Such an array of cores is called a memory plane, and can be joined with other planes to form stacks. The size and number of planes or stacks used in a given computer depend on its designed memory capacity.

The computer industry has called on RCA to supply literally billions of individual cores. *Fig. 1*—a greatly-enlarged drawing—shows one such core threaded with the wires needed to conduct the electrical currents that *read, write, sense* and *inhibit* information in the memory of a typical computer. The memory, in turn, is called upon to store data, read them out on demand, and then write or restore the information for use again and again.

New-generation computers, more and more complex, increase the need for cores that operate at higher speeds. Core size is becoming smaller, but they still must be threaded with multiple wires. This brings a new and greater complexity to the production of cores and ways to include them in planes and stacks. At RCA—a pioneer in memory core technology—chemists, physicists, metallurgists, ceramicists and electronic engineers are all combining their respective disciplines and talents to develop new core materials and new ways to manufacture these tiny magnets—some so small that they would readily pass through the eye of a needle!

RCA advancements include a ferrite material which operates successfully over a range of temperatures from −55° to +125°C, eliminating the need for air conditioning. Another RCA-developed ferrite core needs only very low currents through its network of wires—reducing over-all power demands. A unique RCA development—the *transfluxor*—is shown in *Fig. 2.* It is a two-aperture core designed for use in Electrically Alterable Non-Destructive Read-Out magnetic memories. This device can be programmed electrically from a remote location, in contrast to fixed core types which have to be removed from the computer in order to be given new instructions. Each of these RCA technological advancements holds attractive promise for computer designers in aerospace and military applications as well as scientific and business-oriented data processors.

To manufacture cores of constant, uniform quality, RCA Electronic Components has developed entirely new and highly advanced manufacturing techniques. A new process has reduced the time required to produce and evaluate

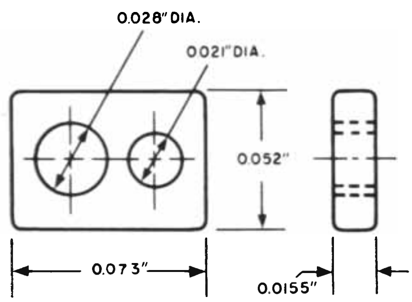


Fig. 2

cores from days to hours. RCA cores are bringing new speed and dependability to planes and stacks for the new generation of high-speed computers.

One such plane is shown in *Fig. 3.* Its specific application is as part of the memory used in a new type of computer developed by American Machine & Foundry Company for use in restaurants. The first drive-in restaurant equipped with this new AMFARE™ computer has just recently gone into operation. At each serving position, the counterman "feeds" information to a centrally-located computer situated behind the scene. He uses a keyboard that au , pre-

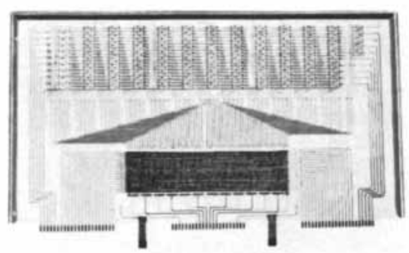


Fig. 3

pares the customer's check, and computes his exact change—all by querying the data stored in the computer memory. The same computer will aid in food-supply audit and inventory control, provide instant cash-flow data to management, and maintain needed tax records. The keyboard used to instruct the computer, and the RCA-made cathode-ray tube which displays the details of each transaction, are shown in *Fig. 4.*

This restaurant computer—latest innovation in mass feeding—shares one important facet with the hundreds and thousands of high-speed computers

Fig. 4

now used in military, scientific, industrial and commercial endeavors. Chances are their high-speed complex memories are built around new-type ferrite cores—the direct result of RCA's pioneering advancements in core materials and technology.

And as a leader in developing and manufacturing memory devices, RCA Electronic Components is already deeply involved with many other memory materials and technologies, as well. (For example, plated-wire memory devices; cryogenic memories using the phenomenon of superconductivity, and advanced solid-state integrated circuit memories.) All of these are under investigation by RCA scientists.

For technical information about current Memory Products, write RCA Electronic Components, Commercial Engineering, Section H95EC, Harrison, N.J. 07029.

RCA

THE AUTHORS

NATHAN S. CAPLAN and JEFFERY M. PAIGE ("A Study of Ghetto Rioters") have been colleagues at the University of Michigan. Caplan is a program associate in the Center for Research on Utilization of Scientific Knowledge, which is part of the Institute for Social Research at the University of Michigan. He is also a lecturer on psychology at the university, where he has served since receiving his Ph.D. from Western Reserve University in 1961. Paige, who was graduated from Harvard College in 1964, has been working with Caplan but is about to become an assistant professor of sociology at the University of California at Berkeley. This year he is receiving his Ph.D. from the University of Michigan after submitting a thesis based on data about ghetto riots. Both Caplan and Paige were consultants to the National Advisory Commission on Civil Disorders.

C. K. N. PATEL ("High-Power Carbon Dioxide Lasers") is a member of the staff of the Bell Telephone Laboratories. Born in India, he was graduated from the College of Engineering of the University of Poona in 1958. From 1958 to 1961 he did graduate work at Stanford University, receiving his master's and doctor's degrees in electrical engineering in 1959 and 1961 respectively. In 1961 he joined Bell Laboratories, where he has done extensive work on lasers. As a result of his work he received in 1966 the Adolph Lomb Medal of the Optical Society of America, which is awarded every two years to a person under 30 years old who has "made a noteworthy contribution to optics." At the time of the award his senior colleagues at Bell Laboratories were quoted as saying that "his theoretical and experimental contributions to gas lasers are equaled by very few scientists regardless of age."

LLOYD J. OLD, EDWARD A. BOYSE and H. A. CAMPBELL ("L-Asparagine and Leukemia") are at the Sloan-Kettering Institute for Cancer Research. Old received his M.D. from the University of California at Berkeley in 1958; Boyse was graduated in medicine from the University of London in 1952, and Campbell, who is a biochemist, received his Ph.D. from the University of Wisconsin in 1939. At the Sloan-Kettering Institute, Old and Boyse began in 1961 a study of the immunology of leukemia in mice. Campbell, who is widely known for the part he played in isolating the anticoagulant dicumarol from spoiled clover in 1941, joined Old and Boyse in 1962.

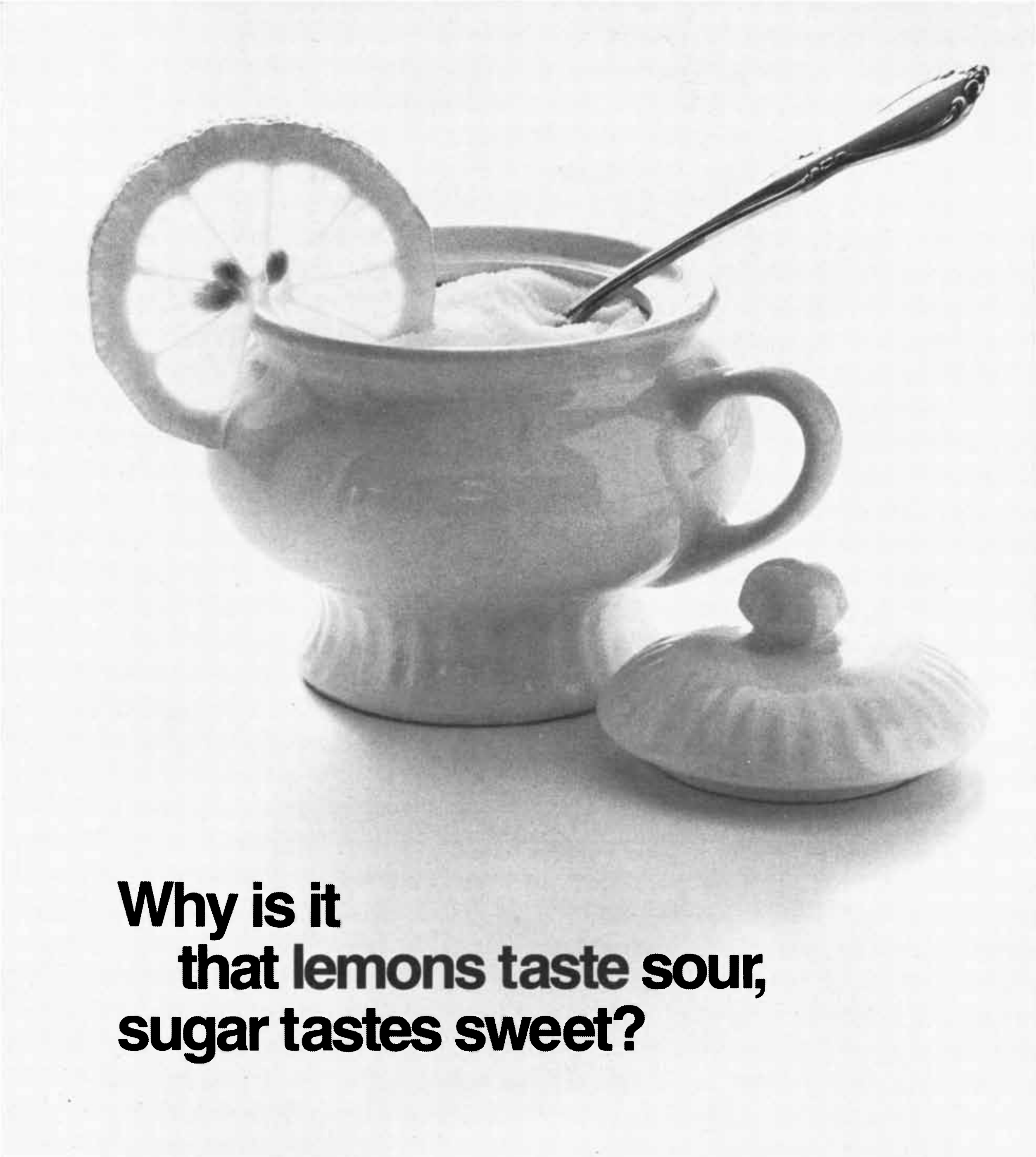
G. NEUGEBAUER and ROBERT B. LEIGHTON ("The Infrared Sky") are respectively associate professor of physics and professor of physics at the California Institute of Technology. Neugebauer was graduated from Cornell University and obtained his Ph.D. from Cal Tech in 1960. After two years as an Army officer, during which time he served at the Jet Propulsion Laboratory, he returned to Cal Tech to pursue work in infrared astronomy. He participated in an infrared radiometric experiment flown past Venus on the spacecraft *Mariner II* and is preparing a similar experiment for the two Mariner spacecraft that will investigate Mars in 1969. Leighton was graduated from Cal Tech in 1941 and received his Ph.D. there in 1947. He worked on cosmic ray physics until about 1960, when his research interests turned toward solar physics and astrophysics. He participated in the television experiment carried out by *Mariner IV* and is working on a more comprehensive television experiment to be included in the Mars spacecraft next year. Neugebauer and Leighton cooperated in the construction and operation of an infrared telescope starting in 1963 and are now planning a larger instrument.

JOHANNES A. KYLSTRA ("Experiments in Water-breathing") is associate professor of medicine and assistant professor of physiology at the Duke University Medical Center. His career has alternated between the Netherlands and the U.S. He was born of Dutch parents in the Netherlands East Indies and educated in the Netherlands, where he received a medical degree from the University of Leiden in 1952. From 1952 to 1954 he was an intern at Albany Hospital in Albany, N.Y., and from 1955 to 1958 he was a lieutenant in the Royal Netherlands Navy Medical Corps. In 1958 he obtained his Ph.D. in physiology from the University of Leiden. After three more years in the U.S. he served from 1961 to 1963 as assistant professor of physiology at the University of Leiden. He was at the State University of New York at Buffalo for two years before going to Duke in 1965.

RAYMOND BLOCH ("The Origins of the Olympic Games") holds the chair of Latin Epigraphy and Roman Antiquities at the University of Paris (the Sorbonne) and is director of the university's École Pratique des Hautes Études. After being graduated from the École Normale Supérieure in 1938 he began teaching at the École Française de Rome. His career was interrupted by World War II: from 1940 to 1945 he was a prisoner of war of the Germans. Returning to the École Française in 1945, Bloch began in 1946 to direct archaeological excavations at Bolsena in Italy. These excavations are continuing, as are excavations near Bologna that he began in 1960 under the auspices of the École Française. Bloch's affiliation with the Sorbonne began in 1949. He was the author of the article "The Etruscans" in the February 1962 issue of SCIENTIFIC AMERICAN.

E. LLEWELLYN THOMAS ("Movements of the Eye") combines experience as a physician and an electrical engineer: he is professor of pharmacology in the faculty of medicine at the University of Toronto and associate professor of electrical engineering in the university's faculty of applied science and engineering. He is also associate director of the Institute of Bio-Medical Electronics, which the two faculties established in 1963 to investigate the application of engineering techniques and concepts to the biological sciences and vice versa. Born in England, Thomas received his engineering education at the University of London and his medical education at McGill University. He has worked as an engineer with the British army and the Montreal Neurological Institute and as a physician in Nova Scotia and also as an investigator of aerospace psychophysiology with the Defence Research Board of Canada.

MARTIN A. LEIBOWITZ ("Queues") is associate professor in the department of applied analysis at the State University of New York at Stony Brook. His training has been in applied mathematics; he received his bachelor's degree at Columbia College in 1956 and his Ph.D. from Harvard University in 1961. From 1960 to 1963 he was with the International Business Machines Corporation, working chiefly on operations research connected with computer and communication systems. From 1963 until he went to Stony Brook in 1966 he was with Bellcomm, Inc., working on control, guidance and trajectory problems in connection with space systems. "Looking back," he writes, "it seems to me that I have worked in a large variety of fields, but there is an underlying thread: they have all involved the application of probability and random processes." He is writing a book about applied random processes.



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A Study of Ghetto Rioters

Why do Negroes riot? An analysis of surveys made after the major riots of 1967 in Detroit and Newark indicates that some of the most familiar hypotheses are incorrect

by Nathan S. Caplan and Jeffery M. Paige

In the summer of 1964 riots broke out in the Negro ghettos of a number of major American cities. Since then rioting has occurred with increasing frequency and intensity. In 1967 there were 164 distinct disturbances; this past April, in the week following the assassination of Martin Luther King, there was violence in more than 100 communities. These disorders present a serious danger. In themselves they threaten to disrupt normal political relations and functions and to alter the quality of urban life; moreover, they are surely symptoms of deep social and economic problems.

What are those problems? Why do Negroes riot? It is important to be accurate in defining the ghetto problem because how we define it determines what we will do about it. Riots are not new in American history, and after each major outburst there have been attempts to make sense of the events by determining their causes. Formal commissions were established in 1919, 1943 and most recently in 1967 for that purpose. The reports of these commissions, the investigations of social scientists and the speculations of the press and the public have produced a number of more or less well-formulated theories as to the causes of riots. The theories differ widely in detail and more widely in degree of sophistication, but it is fair to group them into three major categories.

The first of these categories might be called the "riffraff theory." It holds that rioters are irresponsible deviants: criminals, unassimilated migrants, emotionally disturbed persons or members of an underclass. It sees the rioters as being peripheral to organized society, with no broad social or political concerns, and views the frustration that leads to rioting as simply part of a long history of personal failure.

The second category, which can be called the "relative-deprivation theory," attributes the riots to a gap between the rioters' objective economic and social situation and their expectations—which the outside observer usually considers unrealistic. These expectations are said to result either from the fact that the lot of the Negro is improving, but not rapidly enough ("the revolution of rising expectations"), or from an implicit comparison with the economic situation of whites.

The third category, the "blocked-opportunity theory," sees riots as the consequence of the prolonged exclusion of Negroes from American economic and social life. This theory views white discrimination as a constant barrier to Negro occupational mobility; the Negroes who are most likely to react violently to this barrier are those who want to better themselves and who feel that their own economic and social situation is a result of discrimination rather than of personal inadequacy. It is held that for many years the traditional stereotype of Negro inferiority provided a convenient explanation—both for whites and for blacks—of the socially inferior position of the latter, and that those Negroes who have most thoroughly rejected this stereotype are now most likely to blame white society rather than themselves for their low status and to react violently to their exclusion.

These three theories have important implications for any action taken in response to rioting. The first two theories (particularly the first), by attributing the causes of riots to individuals, relieve white institutions of most of the blame. They suggest that the antidote for rioting is to change the individual rioters through psychotherapy, social work or, if all else fails, prolonged confinement. The third theory suggests that it is not Negro rioters who must be changed but the white institutions that continue to exclude them. Changing these institutions, or the system that legitimizes them, is of course more difficult and less popular politically than establishing remedial programs.

In behalf of the National Advisory Commission on Civil Disorders (the "Kerner Commission"), our group at the Institute for Social Research at the University of Michigan undertook to test these different explanations of riots. We did this by analyzing the characteristics and attitudes of individual rioters as revealed by interview surveys conducted in two cities in which major riots took place during the summer of 1967, Detroit and Newark. In each case the sampling area consisted of the 1960 census tracts in which violence and damage had occurred. To obtain a representative sample one must ensure that each household has an equal probability of being included, but in urban areas it is more efficient and convenient to work with only a few blocks. The best method is to see that each block has a probability of selection proportional to its size (number of dwelling units) and then to see that each unit has a probability of selection inversely proportional to the block size. Since the overall probability of selection of any dwelling unit is the product of these two probabilities, this technique ensures that each unit has a roughly equal chance of being included.

In both cities trained Negro interviewers were assigned to the selected dwelling units. In Detroit they enumerated every person above the age of 15 in each assigned dwelling and selected every other one for interviewing. In Newark they listed the Negro males between 15 and 35 and interviewed them all. The interviewers were persistent, and eventually 67 percent of the eligible respondents were interviewed in Detroit and 66 percent in Newark; the others either could not be found at home after repeated call-backs or (only about 3 percent) refused to be interviewed. These response rates are somewhat lower than those in well-conducted surveys of white middle-class populations but are comparable to rates in other recent ghetto studies.

The first objective was to identify those who had participated in the riots. Two questions were used, one more direct than the other. The indirect question simply asked if the respondent had been active during the disturbance, leaving him free to define "active" as he chose. The other question was "What did you do?" and the interviewer read off a list of behavior ranging from staying at home to sniping. Respondents were classified as "rioters" if they reported that they were active or that they had been involved in breaking windows, looting or fire-bombing and so on. Those who reported that they had stayed at home or had gone out in front of their homes to watch the disturbances were considered "nonrioters." About 11 percent of the 437 respondents in Detroit identified themselves as rioters. In Newark, where all 236 respondents were young men, the figure was 45 percent.

We checked the validity of the rioter-nonrioter classification in two ways and found a high degree of statistical support for the separation into the two categories. One method was to test for internal validity by comparing the answers of the two groups on questions that seemed likely to differentiate between them. For example, when we asked what kinds of sentence should be imposed on looters (or arsonists or snipers), respondents classified as rioters were much more likely than nonrioters to believe no penalty or a lenient one was appropriate. Similarly, more rioters than nonrioters felt that the police should have acted "more gently" when the riots began. We also had a test of external validity that supported the rioter-nonrioter designations: When we compared our respondents with 11,000 people arrested for riot activity in various cities, our rioter group resembled the arrestees more closely on the basis of a number of demographic variables than the nonrioter group did.

Satisfied as to the validity of the rioter-nonrioter categories, we went on to consider the differences in the two groups' responses to a number of questions. The data make possible empirical testing of

DETROIT RIOT lasted for four days in July, 1967. Fires set in stores spread through residential areas, as in this photograph made on July 23. Property damage amounted to $45 million and 43 people were killed, most of them by police and National Guard action.

each of the three major theories of riot participation and thus help us to begin to understand what really motivates the rioters. (In the analysis that follows the differences cited between rioters and nonrioters are statistically reliable unless otherwise noted, and they hold up after age and other relevant demographic factors are controlled.)

According to three principal varieties of the riffraff theory, the rioter is respectively a member of a deprived underclass, an unassimilated recent migrant or an emotionally disturbed person. The first hypothesis argues that the rioters are the "hard core" unemployed—often out of work for long periods of time or chronically unemployable because they lack skill or education. Having lost contact with the job market and all hope of finding work, these people are economically at the very bottom of Negro society, poorly educated even when compared with other ghetto Negroes.

The survey data do not support this hypothesis. There is no significant difference in income between rioters and nonrioters. In Detroit, where we recorded the individual income of male respondents, there was some tendency for rioters to report smaller annual incomes than nonrioters: 39 percent of the rioters and 30 percent of the nonrioters had annual incomes of less than $5,000 per year. Even this small difference disappears when the data are age-controlled, that is, when the fact that boys and young men earn less than older men is taken into account. In Newark, where we asked about family income, the economic status of the two groups is again nearly equal: 33 percent of the rioters and 29 percent of the nonrioters reported family incomes of less than $5,000. These data point up two things, both of which weigh against the riffraff theory. First, differences in economic status do not differentiate rioters from their nonrioting neighbors. Second, the rioters are not the poorest of the poor. Whereas there may be many people with very low incomes who riot, a comparable percentage of people whose incomes are just as low do not.

Among the males in both the Detroit and the Newark surveys, about 30 percent of the rioters reported that they were unemployed. The unemployment rate among the nonrioters differed in the two cities. In Detroit the unemployment rate among the nonrioters was practically identical with that for the rioters, 32 percent. Unemployment among the Newark nonrioters was lower, 19 percent. In addition we found that in Newark 61 percent of the self-reported rioters, but only 43 percent of the nonrioters, had been unemployed for a month or more during the preceding year. (Students were excluded from the analysis of employment data.) We also found that the Newark rioters more often held unskilled jobs: only 50 percent of the rioters and 60 percent of the nonrioters held jobs at the semiskilled level or better.

It is clear from these findings that the rioters are not the hard-core unemployed. In Newark, where we did find some indication of employment differences between rioters and nonrioters, the rioters are more likely to be marginally employed than truly unemployable. As a matter of fact, occupational aspiration was higher among rioters than among nonrioters in Newark. Only 29 percent of the employed rioters (compared with 44 percent of the nonrioters) said they were satisfied with their present job. Seventy-one percent of the rioters and 56 percent of the nonrioters reported that they wanted better jobs. Instead of being those at the bottom of the class structure who have given up hope, it seems that the rioters are continually on the margin of the job market, often employed but never for long.

NEWARK AFTERMATH is shown in a photograph of a street in the business district seven months after the July 1967 riot. The damage total was $10 million, most of it caused by looting and vandalism in stores; 23 people were killed, of whom 21 were Negro civilians.

Nor are the rioters the least educated. In Detroit 93 percent of the rioters remained in school long enough to acquire some high school education; the comparable figure for the nonrioters is 72 percent. In Newark 98 percent of the rioters and only 86 percent of the nonrioters had attended high school. (The differences between the two cities are due to the age differences between samples, with the Newark respondents all under 35.) Probably no single finding in our data argues so strongly against the underclass theory. The finding is precisely the reverse of the prediction. There *is* a significant relation between schooling and riot activity, but it is the rioter who is the better educated! Although it is true that the rioter is likely to be a high school dropout, his nonrioting neighbor is more likely to be an elementary school dropout. Even if all the other assumptions of the underclass theory could be supported, it would require major revision or supplementation because of the finding on education.

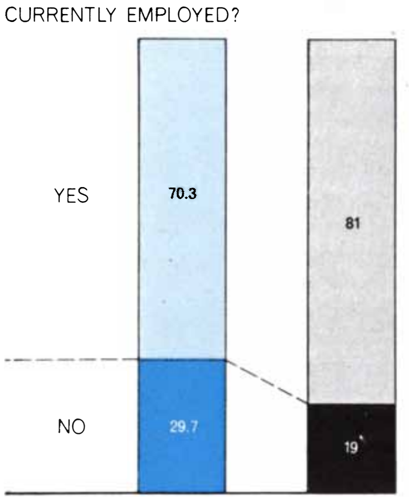
Another riffraff hypothesis is that rioters are most likely to be found among recent migrants to the urban area. The unassimilated migrant is not accustomed to the problems of urban life and is unable to cope effectively with its complexities, it is suggested, and his bewilderment and the pressures of poverty, crime and unemployment produce frustrations that eventually lead to rioting. Certainly the facts on the movement of Negroes from the rural South to Northern cities make such a hypothesis seem reasonable. Since 1910 the proportion of Negroes living in the South has dropped from 90 percent to 55 percent. During the same period the total Negro population of the U.S. has more than doubled and the number living in cities has increased fivefold. This shift in population concentration has been felt primarily in the very Northern metropolitan centers where ghetto rioting has occurred.

In Detroit and Newark, however, we found that those most likely to riot were not the migrants but the long-term residents. In Detroit 59 percent of the rioters and 35 percent of the nonrioters had been born in the city. In Newark the discrepancy was even greater: more than half of the rioters and less than a quarter of the nonrioters were natives.

We focused more closely on the migration question by comparing the region of socialization, or upbringing, for the two riot activity groups. In both Detroit and Newark 74 percent of the rioters reported that they had been raised in the North. Among the nonrioters 64 percent in Detroit and 48 percent in Newark said they were raised in the North. It is, then, the long-term residents—those who know Northern living patterns and the city best—and not the unassimilated migrants who are most likely to riot. Again the prediction of the riffraff theory is reversed.

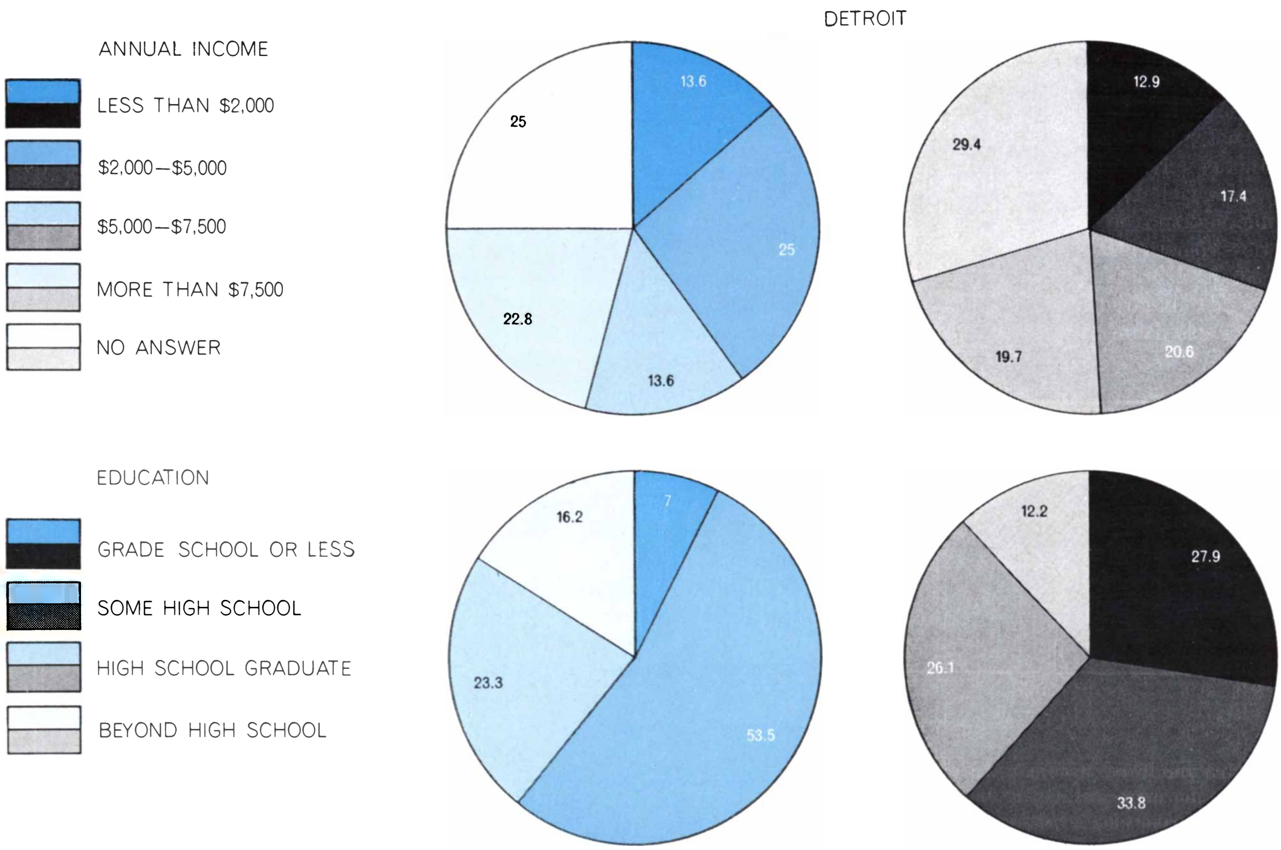
The third riffraff hypothesis maintains that the riots are caused when people whose personalities are vulnerable to stress lose control of their behavior; for such people rioting is a temporary aberration, an opportunity for becoming momentarily elated and free of all care. This psychiatric interpretation, like the other variations of the riffraff theory, attributes riots to people rather than to situations.

Although it is difficult to measure personality characteristics directly in surveys, the data include information about some important social determinants of adjustment. For example, the nuclear family has come to be viewed as an important influence on adult personality,

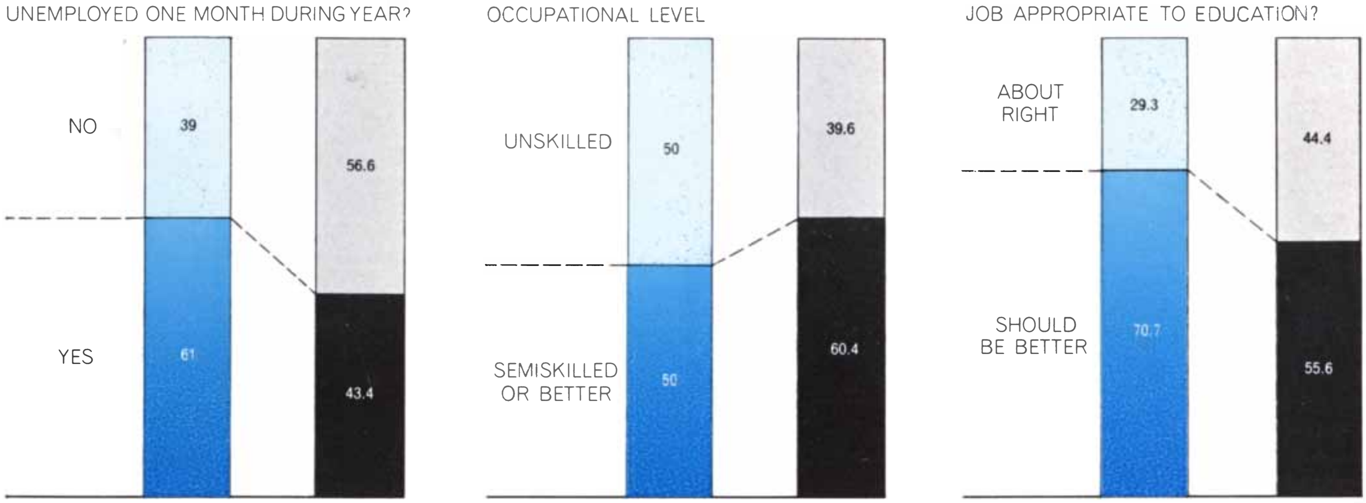


EMPLOYMENT SITUATION in Newark is shown for Negro men aged 15 to 35 classified

and the frequent absence of the father is often cited as a cause of maladjustment among Negroes. In Newark we questioned our respondents about family structure during their childhood, asking if there was an adult male living in the home during that crucial phase of their personality development. There was es-



INCOME AND EDUCATION statistics for Detroit and Newark contradict the "riffraff theory" on riot participants. The income breakdown (*top*) shows few significant differences between rioters (*color*) and nonrioters (*gray*). (In Detroit the individual income



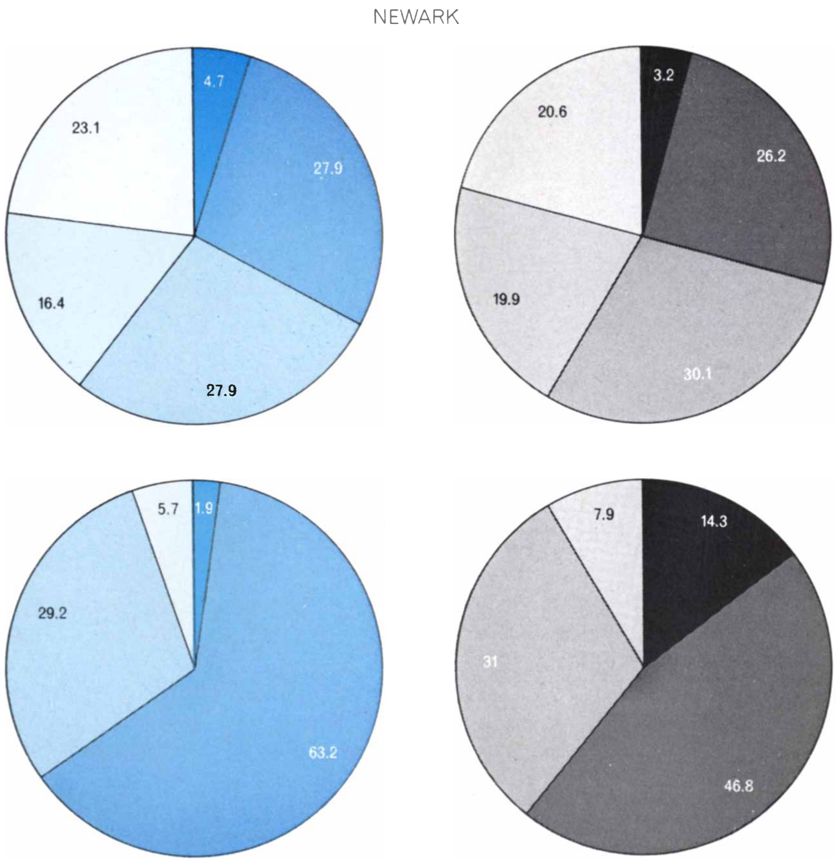
as rioters (*color*) and nonrioters (*gray*). The rioters tended to be marginally employed. Asked if their jobs were "appropriate considering the education you have," rioters more often answered that they should have a "job with more income and responsibility."

sentially no difference between rioters and nonrioters in the response to this question. Almost 75 percent of the rioters and 77 percent of the nonrioters reported the presence of an adult male in their home during their childhood.

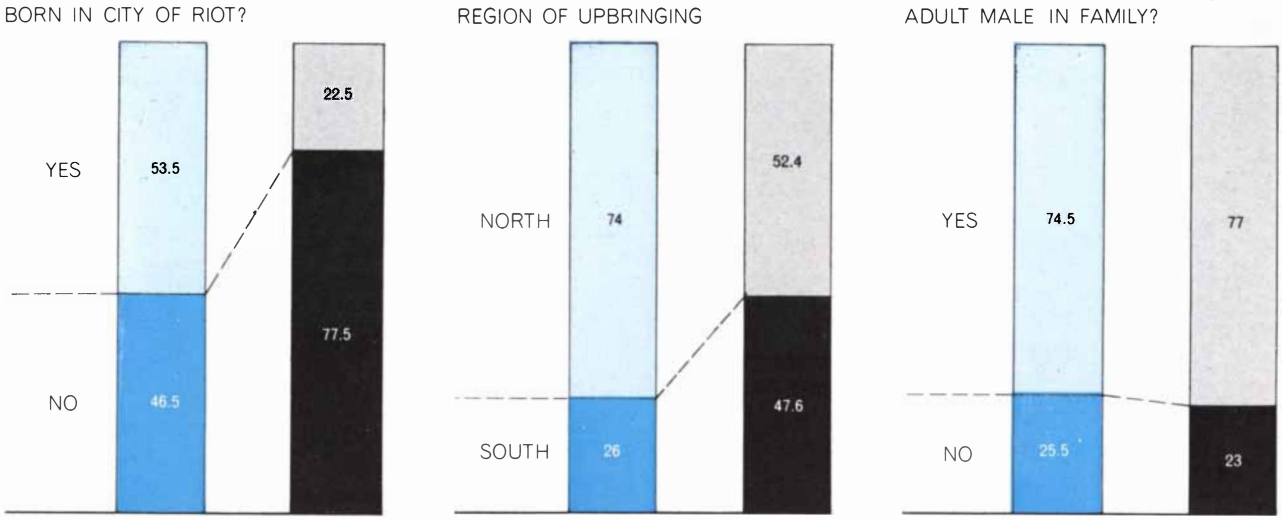
We also have several indicators of the respondents' social behavior under ordinary circumstances. In Newark, where we questioned men about their membership in organizations, we found a slight tendency for rioters to hold a larger number of group memberships and no difference between rioters and nonrioters in the types of group memberships held. In Detroit we asked about social interaction with neighbors. Again we found a slight tendency for rioters to be more active than their nonrioting neighbors: 35 percent of the rioters but only 17 percent of the nonrioters reported daily visits with their neighbors. When we questioned the Newark respondents on the regularity of their church attendance, we found no differences between the groups, rioters and nonrioters alike reporting an average attendance of two or three times a month. The information from these items does not indicate that the rioter is alienated from or peripheral to the larger Negro community.

In Detroit we had questions intended to show whether or not rioting is related to differences in support for an important American value: belief in work and the Protestant ethic. Rioters and nonrioters were virtually identical in their responses to most of these questions. For example, when we asked, "Is getting what you want out of life a matter of ability or being in the right place at the right time?" 77 percent of the rioters and 76 percent of the nonrioters said it was "ability."

We have examined the riffraff theory from a number of different viewpoints and have found that the Newark and Detroit survey data do not support it. The rioters are not the poorest of the poor. They are not the hard-core unemployed. They are not the least educated. They are not unassimilated migrants or newcomers to the city. There is no evidence that they have serious personality disturbances or are deviant in their social behavior. They do not have a different set of values. None of these factors sets the rioter off from the rest of the community in a way that justifies consid-



of respondents was reported, in Newark the family income.) Educational findings (*bottom*) were the reverse of what might have been expected: Rioters had more years of high school.



RIFFRAFF THEORY is also belied by results on migration and upbringing. As these Newark findings show, rioters (*color*) were less likely than nonrioters to be migrants from the South and were no more likely to have been brought up without a man in the family.

ering him a personal failure or an irresponsible person. In fact, on some of the "prosocial" items, such as education and occupational aspiration, the rioter compares favorably with the nonrioter or even surpasses him.

The relative-deprivation theory has two major forms. The first of these is based on a motivational finding that has been known for a long time in psychology: the closer one comes to reaching a goal, the greater the frustration of not attaining it. According to this "rising expectations" point of view, riots should take place not when things are at their worst but when things are getting better —but not fast enough. Such an explanatory model holds up well in the study of revolutions; they are usually born of hope, not despair. The French Revolution, for example, occurred during a period of unprecedented economic growth, and it was not those in abject poverty who revolted but the rising middle class.

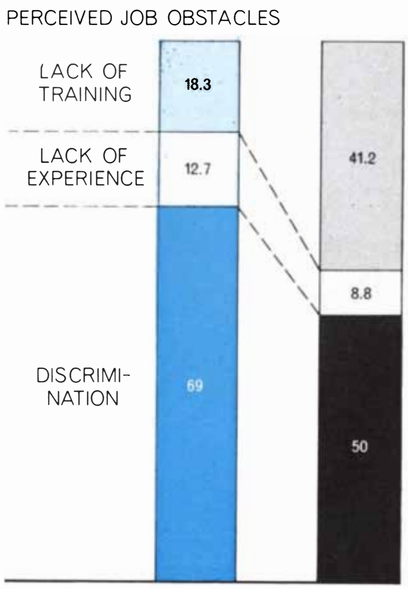
However serviceable this theory may be in describing the environment of revolution, it does not serve to distinguish the individual rioter. If it did, we would find that those whose economic situations had improved most dramatically were the most likely to riot. In Newark we asked respondents if things had got better or worse or had remained the same for them and their families over the past few years; we found no differences between the responses of rioters and nonrioters.

A second version of the relative-deprivation theory is based on the economic and social gap between Negroes and the majority of whites. The assumption here is that members of the black community are concerned not so much with what they have as with what they feel they deserve compared with the whites; attention to the discrepancy arouses a sense of social injustice that generates the frustration leading to rioting.

In Newark we asked: "How about the gap in income between Negroes and whites? Do you think that in Newark it is increasing, decreasing or not changing?" There was no real difference in response between the groups, with 36 percent of the rioters and 38 percent of the nonrioters reporting that the gap was increasing. On the other hand, we did find a statistically reliable difference between rioters and nonrioters when we questioned them about incomes within the Negro community. We asked respondents if they thought that "the gap between those Negroes who are better off in Newark and those who are poorer is increasing, decreasing or not changing." Thirty-nine percent of the rioters and only 27 percent of the nonrioters reported that the gap was increasing, providing support for the relative-deprivation theory in an unexpected way: Rioters are particularly sensitive to where they stand in relation to other Negroes, not to whites.

The blocked-opportunity theory, unlike the other two theories, emphasizes environmental rather than personal factors as the cause of riots. Specifically, it stresses the exclusion of Negroes from white society. If this theory accurately explains the rioting, we would expect rioters to be more sensitive to discrimination and to report that they experience it more frequently in areas of achievement such as education and employment. We would also expect them to be more likely to reject the traditional stereotype of Negro inferiority. Each of these predictions is in fact borne out by the survey data.

Asked if they felt they could find the kind of job they wanted and if not why not, rioters were more likely to say that such jobs were not available to them and that the reason was racial discrimination rather than lack of education and training. We found that 69 percent of the rioters but only 50 percent of the nonrioters in Newark said racial discrimination constituted the major obstacle to better employment. Furthermore, more than half of the rioters, as compared with less than a third of the nonrioters, felt



RIOTERS (*color*) were more bitter than nonrioters in Newark, more likely to blame they had been discriminated against in school.

Both the Detroit and the Newark surveys indicate that rioters have strong feelings of racial pride and even racial superiority. They not only have rejected the traditional stereotype of the Negro but also have created a positive stereotype. Asked "Who do you think are smarter people, Negroes or whites?" 53 percent of the Detroit rioters and only 26 percent of the nonrioters chose Negroes; in Newark 44 percent of the rioters and only 29 percent of the nonrioters called Negroes smarter. We also asked: "Who do you think are more dependable, Negroes or whites?" In Detroit 45 percent of the rioters but only 19 percent of the nonrioters rated Negroes more dependable, as did 39 percent of the rioters and 24 percent of the nonrioters in Newark. Similarly, the rioters were more likely to consider Negroes "braver" and "nicer" than whites.

In Newark we asked two additional items related to racial identity, and here again the responses reflect a higher level of racial pride among rioters. Significantly more rioters preferred to describe themselves as "black"—a word that has become a badge of racial pride and militancy—rather than as "Negro" or "colored." Half of the rioters and only a third of the nonrioters preferred to be called black. Similarly, we found a tendency for rioters to be stronger in the belief that all Negroes should study African history and language: 80 percent of the rioters and 68 percent of the nonrioters thought these subjects should be taught.

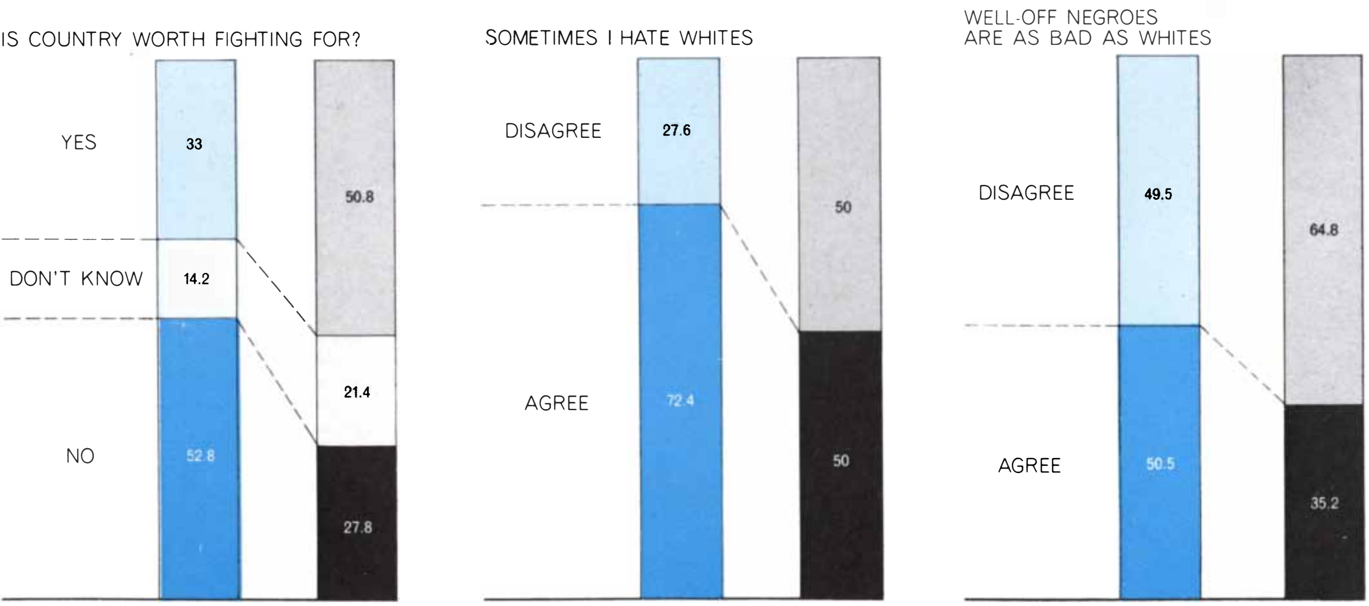
This group of results explains the otherwise puzzling finding that rioters are more often from the North. An analysis of the data by region of upbringing showed that those who grew up in the South had less racial pride, were much more likely to blame their failures on lack of education or training rather than on discrimination and were less likely to say they had experienced discrimination in the North. Apparently growing up within the caste system of race relations in the South produces a passive adjustment to exclusion and an acceptance of discrimination as an inevitable and unchanging part of life. The Southern-born Negro is therefore unlikely to challenge the more subtle system of discrimination he finds in the North.

The rioter's anger at a society he views as excluding him is best expressed by the responses to this question: "If the United States got into a big world war today would you personally feel this country is worth fighting for?" Thirty-nine percent of the Detroit rioters, but only 15 percent of the nonrioters, said the country was not worth fighting for. In Newark 53 percent of the rioters and 28 percent of the nonrioters said the country was not worth fighting for.

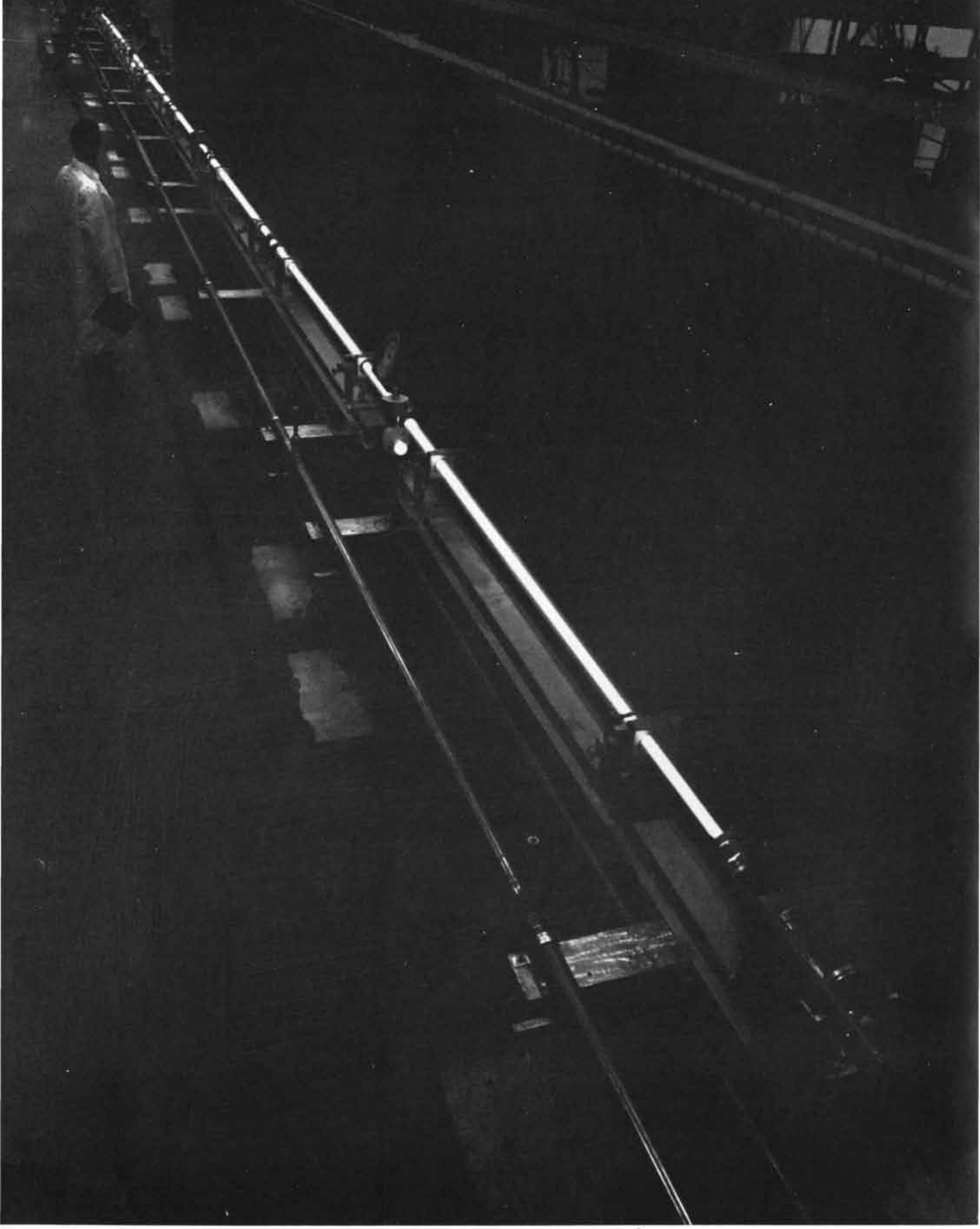
It should be emphasized that the rioters' anger is not simply a result of hostility to whites as a racial group. Instead it seems to be a general resentment of established members of U.S. society, black and white. The survey data indicate that rioters are as resentful of more affluent Negroes as they are of whites. In Newark respondents were asked if they thought that "Negroes who make a lot of money are just as bad as white people." More than half of the rioters but only a third of the nonrioters agreed with the statement. The rioters' resentment seems to cut across racial lines.

The survey data support the blocked-opportunity theory. One is led to conclude that the continued exclusion of Negroes from American economic and social life is the fundamental cause of riots. This exclusion is a result of arbitrary racial barriers rather than of lack of ability, motivation or aspiration on the part of Negroes, and it is most galling to young Negroes who perceive it as arbitrary and unjust.

One important question remains to be answered: "Why do they riot now?" After all, the opportunity structure has been closed for 100 years. Our data suggest that Negroes who riot do so because their conception of their lives and their potential has changed without commensurate improvement in their chances for a better life. In addition to abandoning the traditional stereotype that made nonachievement and passive social adaptation seem so natural, they have developed a sense of black consciousness and a desire for a way of life in which they can feel the same pride and sense of potency they now derive from being black. Negroes are still excluded from economic opportunity and occupational advancement, but they no longer have the psychological defenses or social supports that once encouraged passive adaptation to this situation. The result has been the most serious domestic violence in this century.



discrimination as an obstacle to employment and to agree that "sometimes I hate white people." Fewer rioters felt the country is "worth fighting for in a major world war." Rioters showed more distrust than nonrioters of Negroes "who make a lot of money."



CARBON DIOXIDE LASER 178 FEET LONG, shown in operation at the U.S. Army's Redstone Arsenal in Huntsville, Ala., is capable of producing a continuous beam of coherent light with an output power as high as 2.5 kilowatts. The glow inside the laser tube is caused by the electric discharge used to excite the carbon dioxide gas. The laser beam itself is infrared and hence invisible.

High-Power Carbon Dioxide Lasers

Lasers in which the active medium consists of a low-pressure gas of carbon dioxide molecules have been used to produce the most powerful continuous laser beams achieved to date

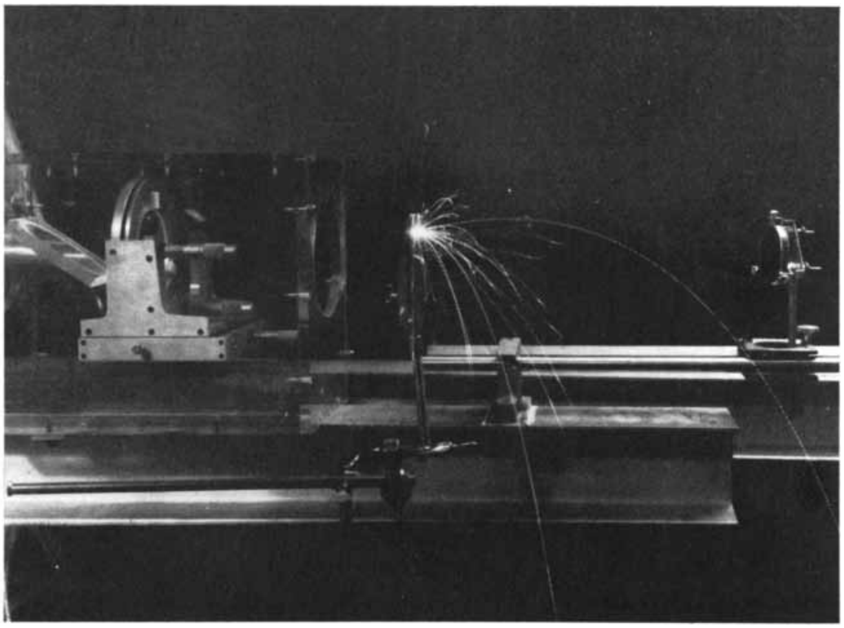
by C. K. N. Patel

Until quite recently it was generally assumed that the most powerful lasers that would ever be built would be solid-state lasers, for the simple reason that in a solid the "lasing" particles are much more concentrated than they are in a gas. Nevertheless, it was recognized almost from the beginning that solid-state lasers have their drawbacks. With respect to two important criteria of laser performance—the spectral purity and the spatial coherence of the output light beam—solid-state lasers rate rather poorly. Moreover, most high-power solid-state lasers operate only in the pulsed mode; in other words, their power output consists of short, intense bursts of light rather than a continuous beam. In contrast the original atomic-gas lasers produced continuous beams with excellent spectral purity and spatial coherence, but their power output was very low compared with the power output from the solid-state lasers.

This situation has changed entirely with the advent of the molecular-gas lasers. The outstanding example of this new class of lasers is the carbon dioxide laser, which can produce a continuous laser beam with a power output of several kilowatts while at the same time maintaining the high degree of spectral purity and spatial coherence characteristic of the lower-power atomic-gas lasers. A carbon dioxide laser was recently used to produce an infrared beam with an output power of 8.8 kilowatts—the most powerful continuous laser beam achieved to date. The significance of such a power output is vividly demonstrated by the fact that a focused infrared beam of a few kilowatts is capable of cutting through a quarter-inch steel plate in a matter of seconds [*see illustration at right*].

Because of their high power output in the infrared region of the electromagnetic spectrum, the carbon dioxide gas lasers have opened up a whole new range of wavelengths for the study of nondestructive optical interactions with gases, liquids and solids. Such optical interactions include nonlinear processes whereby one can generate a coherent source of infrared radiation that is continuously tunable over a range of frequencies. There are in addition a variety of other applications for which high-power carbon dioxide lasers promise to be useful. Perhaps the most important potential application is in the area of optical communications and optical radar. The carbon dioxide laser is particularly suited for use in both terrestrial and extraterrestrial communication systems because the infrared beam it produces is only slightly absorbed by the atmosphere. In this article I shall attempt to explain the physics underlying the operation of this new type of high-power gas lasers.

In general a gas laser consists of a low-pressure gas-filled vessel (called the laser tube) located between two mirrors that form an "optical cavity." The gas in

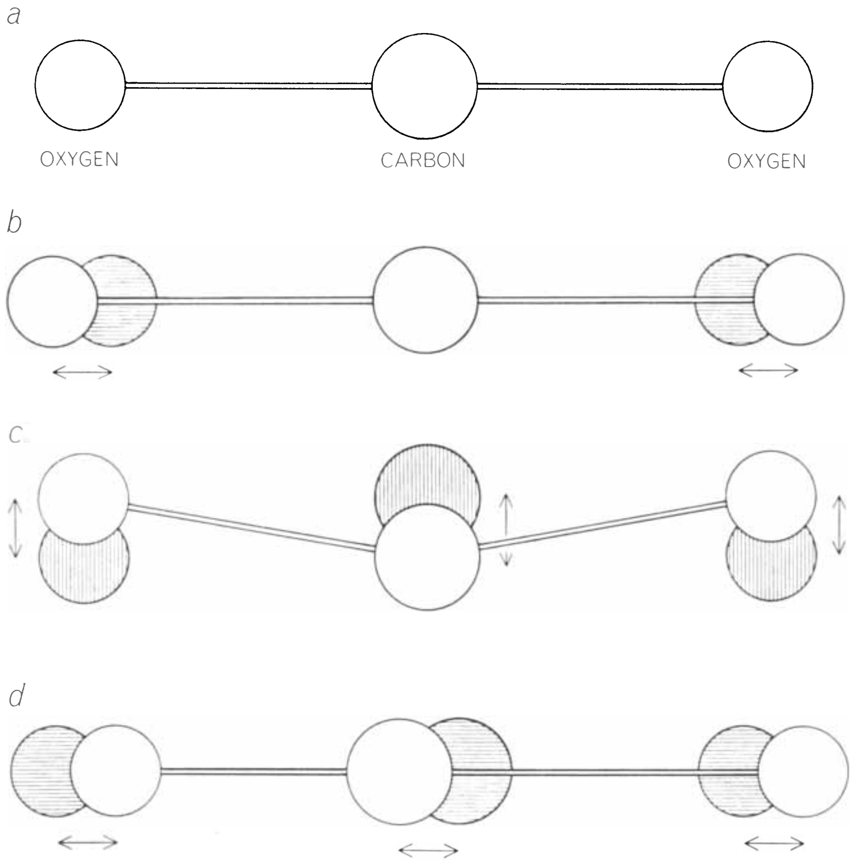


HIGH-POWER INFRARED BEAM from the Redstone Arsenal carbon dioxide laser is shown burning a hole through a quarter-inch-thick stainless-steel plate—a job that takes about 10 seconds. The infrared beam emerges through the slanted Brewster window at the end of the laser tube (*left*) and passes through a partially reflecting end mirror before striking a concave mirror (*right*), which focuses it on the steel plate (*center*). The thermal applications of the high-power carbon dioxide lasers hold considerable promise for industry but are regarded as secondary to the potential use of such lasers in optical communication systems.

the tube (called the laser medium) can consist of atoms, metallic vapor or molecules. Laser action is usually obtained in the gas by subjecting it to an electric discharge; the energetic electrons provided by the discharge collide with the active gas particles, exciting them to higher energy levels from which they spontaneously descend to lower energy levels, emitting their excess energy in the form of photons, or light quanta. In order to achieve the optical "gain" that characterizes laser action it is necessary that the "population density" of particles in the upper energy level exceed that in the lower energy level. This condition is known as population inversion, since it is the inverse of the normal, or nonexcited, state of affairs. In order to achieve a high output power on a given transition between a pair of energy levels, it is also necessary that the absolute number of atoms excited to the upper laser level be large and that the gas particles leave the lower laser level just as fast as they arrive from the upper level. In other words, the "depopulation," or de-excitation, of the particles in the lower laser level is just as important as the excitation of particles from the ground state to the upper laser level, since a particle that has already contributed to the laser output must return to the ground state before it is available again for excitation to the upper level in order to produce additional laser power.

The energy expended by particles in dropping from the lower laser level back to the ground state contributes nothing to the power output of the laser. Hence a certain amount of energy is wasted for every particle that makes the laser transition. This fact suggests an obvious yardstick for judging the efficiency of a particular laser system. The amount of energy wasted by a particle in returning from the lower laser level to the ground state is equal to the difference between the energy needed to excite the particle to the upper laser level and the energy of the photon of light that is emitted when the particle makes the transition from the upper laser level to the lower laser level. It follows that the ratio of these two quantities—the emitted energy divided by the excitation energy—is a measure of the efficiency with which a given laser system can operate. The situation in which every particle that is excited to the upper laser level contributes one photon of laser radiation is of course ideal; it assumes that other mechanisms, such as transitions to other lower energy levels, are negligible for de-exciting a particle in the upper laser level. Thus the ratio of the energy of the emitted photon to the energy of excitation is actually the absolute maximum efficiency (or, as it is sometimes called, the quantum efficiency) of the laser system.

In practice the efficiency of an operating gas laser is considerably lower than its quantum efficiency, since no perfect means exist for selectively exciting the gas particles from the ground state to the upper laser level. Take the case of excitation by means of a collision between an atom and an energetic electron in a gas discharge. The electron must have a certain energy to excite the atom to the upper laser level. Unfortunately in a gas discharge the electrons do not all have the same kinetic energy; instead they are distributed continuously over a wide range of kinetic energies. Hence one cannot help but excite atoms not only to the upper laser level but also to other levels (either higher or lower than the upper laser level), from which they would not contribute to the laser output. The result is that only a fraction of the input electric power needed to produce the discharge is effective in exciting the atoms to the upper laser level. If we define the working efficiency of a laser as the ratio of the output power of the laser beam to the input power of the electric discharge, then the working efficiency will always be much lower than the quantum efficiency. The closer a laser approaches the ideal system in terms of the selectivity of the excitation mechanism, the closer the working efficiency will approach the quantum efficiency. Or, in a somewhat different perspective, a high quantum efficiency, combined with a selective excitation mechanism, is the prescription for obtaining a high working efficiency in a practical laser.

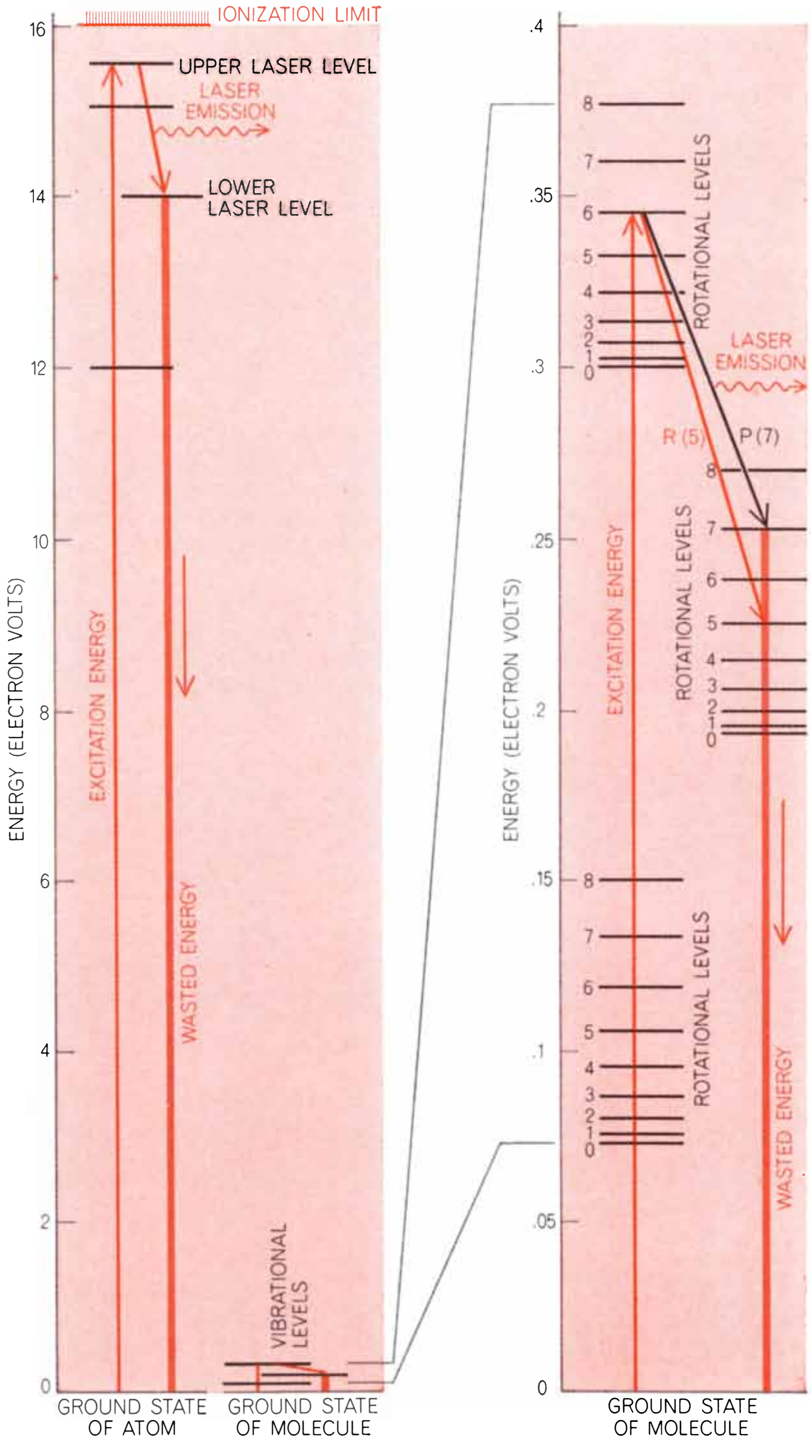


CARBON DIOXIDE MOLECULE (a) is linear and symmetric in configuration and has three degrees of vibrational freedom. In the symmetric stretch mode (b) the atoms of the molecule vibrate along the internuclear axis in a symmetric manner. In the bending mode (c) the oscillation of the atoms is perpendicular to the internuclear axis. In the asymmetric stretch mode (d) the atoms vibrate along the internuclear axis in an asymmetric manner. The vibrational state of the molecule is accordingly described by three quantum numbers, ν_1, ν_2 and ν_3, and is usually written in the form ($v_1v_2v_3$), where v_1 describes the number of vibrational quanta in the symmetric stretch mode, v_2 the number of vibrational quanta in the bending mode and v_3 the number of vibrational quanta in the asymmetric stretch mode.

The first gas laser was operated at the Bell Telephone Laboratories in 1961. It operated on a transition between two excited states of atomic neon and produced a strong laser oscillation at a wavelength of 1.15 microns. Laser action has since been obtained using almost all the elements and covering the wavelength range from 2,000 angstrom units (.2 micron) in the ultraviolet region of the spectrum to 133 microns in the infrared region.

The energy-level spectra of molecular gases are considerably more complicated than those of atomic gases. In addition to the familiar electronic energy levels, a molecule can also have energy levels arising from the vibrational motion and the rotational motion of the molecule [*see illustration at right*]. Thus for a given electronic configuration of a diatomic (two-atom) molecule, say, there are several almost equally spaced vibrational energy levels, and for each of the vibrational levels there are a number of rotational levels. The spacings of the electronic energy levels for molecules are comparable to those for atoms, but the vibrational and rotational spacings are typically smaller by factors of 20 and 500. As a result the energy-level scheme of a molecular gas is extremely complicated.

The first molecular-gas laser oscillation was obtained from electronic transitions of a number of diatomic gases. Obviously, however, one can also have transitions between two different vibrational levels of the same electronic level of the molecule. Such transitions in turn actually occur between two rotational levels belonging to the two different vibrational levels. Moreover, because of the increasing spacing of the rotational levels in a vibrational level and because of a quantum-mechanical selection rule that in the simplest case allows only those transitions involving a change in the rotational angular momentum equal to $\pm h/2\pi$ (h is Planck's constant), such transitions between two vibrational levels result in a vibrational-rotational band [*see illustration on next page*]. The center of the band corresponds to the spacing between the vibrational levels in the absence of any rotational energy; the transitions on the long-wavelength side correspond to a change of $+h/2\pi$ in angular momentum and are called the *P*-branch transitions, whereas those on the short-wavelength side involve a change of $-h/2\pi$ in angular momentum and are called the *R*-branch transitions. As the illustration shows, the *P*-branch and *R*-branch transitions are almost equally spaced. These vibrational-rotational transitions, which usually result in infrared emission, are the basis of all the current breed of high-power molecular-gas lasers.



ENERGY-LEVEL DIAGRAMS of an atom and a molecule are compared. In an atom the electronic energy levels between which infrared transitions can occur are situated near the atomic ionization limit—far above the ground state of the atom. As a result the atom has to be excited to a very high energy in order to produce laser action, which in turn results in the emission of a photon with a comparatively small amount of energy. Thus the use of atomic gases wastes a great deal of energy and results in a low quantum efficiency. In a molecule, on the other hand, the vibrational levels of the electronic ground state are very close to the ground level of the molecule; hence the photon energy is a sizable fraction of the total energy needed to excite the molecule from the ground state to the upper laser level. This results in a much higher quantum efficiency. The enlargement at right shows that the vibrational levels of the molecule's electronic ground state are in turn composed of a number of rotational energy levels due to the rotation of the molecule. The number with each level indicates that level's rotational angular momentum in units of $h/2\pi$. Two of the allowed infrared transitions between the rotational levels belonging to two different vibrational levels are indicated.

I should like to explain now how it was that I came to build and operate the first continuous-wave molecular-gas vibrational-rotational laser at Bell Laboratories a few years ago. In the course of our investigation of laser action in atomic gases it became clear that if the aim was to obtain large power output in the infrared region (that is, at wavelengths longer than a few microns), the atomic gases were far from the ideal system. This is primarily so because for most atomic gases the electronic energy levels between which infrared transitions can occur are situated close to the atomic ionization limit—far above the ground state of the atom. As a result the atom has to be excited to a very high energy level in order to produce laser action, which in turn results in the emission of a photon with a comparatively small amount of energy. Thus the use of atomic gases results in a low quantum efficiency and consequently a low working efficiency.

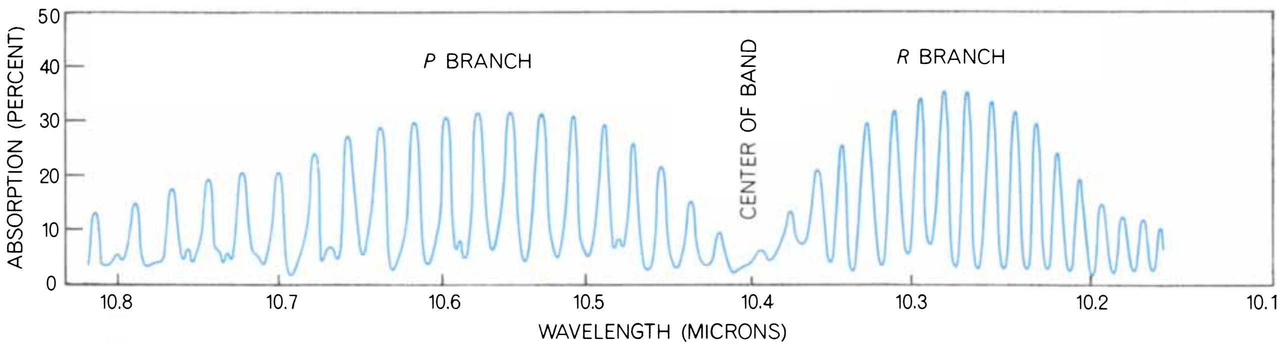
Such a system has another very serious drawback. Close to the ionization limit of an element the energy levels corresponding to different electronic configurations are situated in a very small energy range; as a result electron-impact excitation, which is the mechanism for producing laser action in gas discharges, would be highly nonselective and the population density of atoms in the upper laser level would be very small. This will further limit the power output and result in an even lower working efficiency, since a significant fraction of the energetic electrons capable of exciting atoms to the upper laser level are lost in exciting atoms to other levels nearby. Typically an atomic-gas laser operating at a wavelength of about 10 microns produces only a few milliwatts of power and has a working efficiency of about .001 percent.

The situation is entirely different when one is dealing with molecules; the vibrational-rotational levels belonging to the electronic ground state of a molecule are ideal for efficient and powerful laser systems in the infrared region. The vibrational levels of the electronic ground state are very close to the ground level of the molecule and thus the laser photon energy is a sizable fraction of the total energy needed to excite the molecule from the ground state to the upper laser level. The result is a very high quantum efficiency compared with that of an atomic-gas infrared laser. In addition, since the vibrational levels are close to the ground state of the molecule, almost all the electrons present in a discharge will be effective in the required excitation process. This fact ensures a high working efficiency as well as a high power output, because now one can obtain a large population density of molecules in the upper level.

It was on this basis that I originally decided to investigate the possibility of laser action using the vibrational-rotational transitions of the electronic ground state of carbon dioxide. Diatomic molecules appeared to be less suitable for continuous-wave laser oscillation because of the unfavorable lifetime of diatomic molecules excited to the various vibrational levels of the electronic ground state. Carbon dioxide was chosen for two reasons: it is one of the simplest of the triatomic molecules, and a large amount of spectroscopic information already existed about its vibrational-rotational transitions. The carbon dioxide molecule is linear and symmetric in configuration and has three degrees of vibrational freedom [*see illustration on page 24*]. In one degree the atoms of the molecule vibrate along the internuclear axis in a symmetric manner. This mode of vibration is called the symmetric stretch mode and is denoted ν_1. In another symmetric mode of vibration the oscillation of the atoms is perpendicular to the internuclear axis. This mode is called the bending mode and is denoted ν_2. Finally, there is an asymmetric stretch mode of vibration along the internuclear axis; this mode is denoted ν_3. By the rules of quantum mechanics the energies of the vibrations are quantized and are all different.

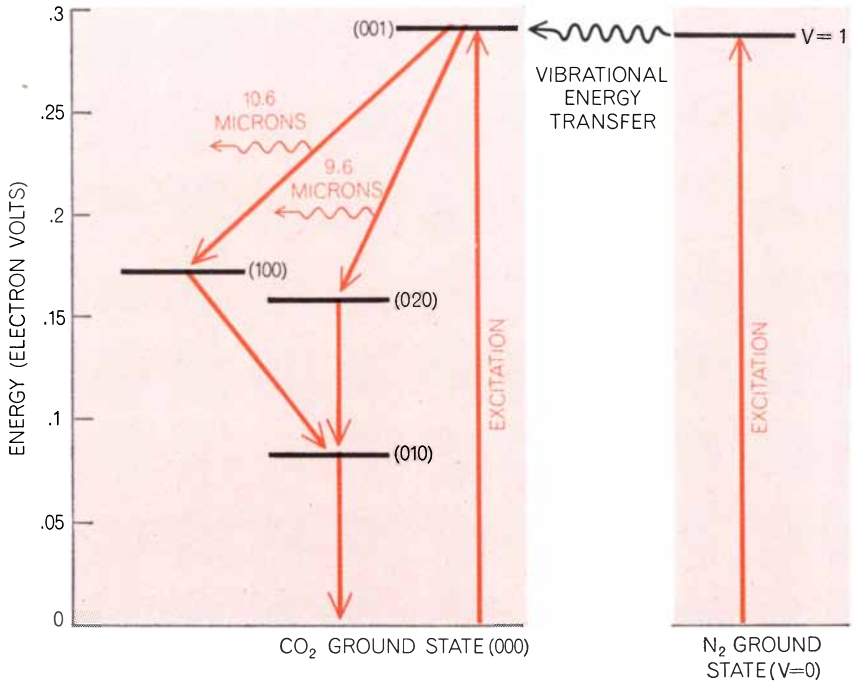
In the first approximation these three modes of vibration are independent of one another. As a consequence the carbon dioxide molecule can be excited to have any linear combination of the three individual modes of vibration. Therefore the vibrational state of the molecule must be described by three quantum numbers, v_1, v_2 and v_3, which represent the quanta of the ν_1, ν_2 and ν_3 modes of vibration to which the molecule is excited. The description of a given vibrational level would accordingly take the form $(v_1v_2v_3)$, where v_1 describes the number of vibrational quanta in the symmetric stretch mode, v_2 the number of vibrational quanta in the symmetric bending mode and v_3 the number of vibrational quanta in the asymmetric stretch mode.

In the energy-level diagram of some of the low-lying vibrational states of carbon dioxide [*see illustration on opposite page*] the rotational substructure of each of the vibrational levels has been excluded in order to keep the diagram relatively uncluttered. The rotational levels are spaced much closer than the vibrational



LASER OSCILLATION arising from transitions between two rotational energy levels belonging to two different vibrational levels of the same electronic level of carbon dioxide leads to the emission of infrared light at a number of different wavelengths, which form what is called a vibrational-rotational band. The curve shows the positions of the transitions as observed in the absorption spectroscopy of unexcited carbon dioxide gas. The center of the band corresponds to the spacing between the vibrational levels in the absence of any rotational energy; the transitions on the long-wavelength side correspond to a change of $+h/2\pi$ in rotational angular momentum and are called the *P*-branch transitions, whereas those on the short-wavelength side involve a change of $-h/2\pi$ in rotational angular momentum and are called the *R*-branch transitions (h is Planck's constant). The band shown here produces 10.6-micron radiation.

states. The various vibrational levels with different quanta in modes ν_1, ν_2 and ν_3 form almost equally spaced ladders, although only the lowest states (those with only one or two quanta of vibrational energy) are shown. For a number of reasons, such as the lifetime of carbon dioxide molecules in various states and the probability of excitation by electron impact from the ground state, the level designated 001 is suitable for the upper laser level, and the 100 and 020 levels form the lower laser levels. The molecules that arrive at the lower levels decay to the ground state through radiative and collision-induced transitions to the lower 010 level, which in turn decays to the ground state. The 001 → 100 vibrational-rotational transitions produce infrared radiation near 10.6 microns, and the 001 → 020 transitions produce infrared radiation near 9.6 microns. Accordingly the quantum efficiency of a 001 → 100 laser would be nearly 40 percent, whereas that of a 001 → 020 laser would be about 45 percent. It is this high quantum efficiency and the possibility of selective excitation to levels that are close to the ground level that originally made the system attractive to investigate and that has made it possible for us to reach practical efficiencies on the order of 20 to 30 percent.



ADDITION OF NITROGEN GAS to a carbon dioxide laser results in the selective excitation of the carbon dioxide molecules to the upper laser level. Since nitrogen is a diatomic molecule it has only one degree of vibrational freedom; hence one vibrational quantum number (v) completely describes its vibrational energy levels. Nitrogen molecules can be efficiently excited from the $v = 0$ level to the $v = 1$ level by electron impact in a low-pressure nitrogen discharge. Since the energy of excitation of the $N_2(v = 1)$ molecule nearly equals the energy of excitation of the CO_2(001) molecule, an efficient transfer of vibrational energy takes place from the nitrogen to the carbon dioxide in collisions between $N_2(v = 1)$ molecules and CO_2(000) molecules. In such a collision the nitrogen molecule returns from the $v = 1$ level to its ground state by losing one quantum of its vibrational energy, thereby exciting the carbon dioxide molecule from its ground state to the 001 level. The carbon dioxide molecule can then radiatively decay to either the 100 level or the 020 level, in the process emitting infrared light at 10.6 or 9.6 microns respectively.

In our earliest experiments the laser tube was filled with pure carbon dioxide at a pressure of about one torr (one millimeter of mercury). The electric discharge was produced by applying a high-voltage direct current across a section of the tube. In such a discharge a large number of collisions occur between energetic electrons and the carbon dioxide molecules. A few of the most energetic electrons cause the carbon dioxide molecules to dissociate, that is, to break up into carbon and oxygen atoms. The threshold for this process, however, is quite high, and the number of electrons possessing this large amount of kinetic energy is very small. The lower-energy electrons, which far outnumber the high-energy electrons, cause the carbon dioxide molecules to be excited to various vibrational levels. As it happens, the electrons preferentially excite the carbon dioxide molecules to the $00v_3$ levels, that is, to the almost equally spaced levels of the ν_3 ladder.

It should be remembered that the upper level for the laser oscillation at 10.6 microns is the one with v_3 equal to 1. Does this mean that the carbon dioxide molecules that are excited to the higher states of $00v_3$ (those with v_3 greater than 1) will not contribute to laser action, thereby reducing the efficiency and power output of the system? In reality this does not happen because the $00v_3$ levels are almost equally spaced, and as a consequence a collision between a $CO_2(00v_3)$ molecule and a CO_2(000) molecule results in an efficient transfer of vibrational energy from the excited molecule to the unexcited molecule. The $CO_2(00v_3)$ molecule loses one quantum of ν_3 vibrational energy and becomes a $CO_2(00v_3 - 1)$ molecule, while the CO_2(000) molecule gains that quantum of energy and becomes a CO_2(001) molecule, or in other words a molecule in the upper laser level [*see upper illustration on next two pages*].

This process is resonant in the sense that there is a redistribution of the energy of the excited molecule without any loss of the total internal energy by its conversion into kinetic, or thermal, energy. This means that the efficiency of converting the $CO_2(00v_3)$ molecules into CO_2(001) molecules with no loss of energy is very high. Therefore in practice one should be able to excite carbon dioxide molecules to the required upper laser level quite efficiently by electron impact in a gas discharge.

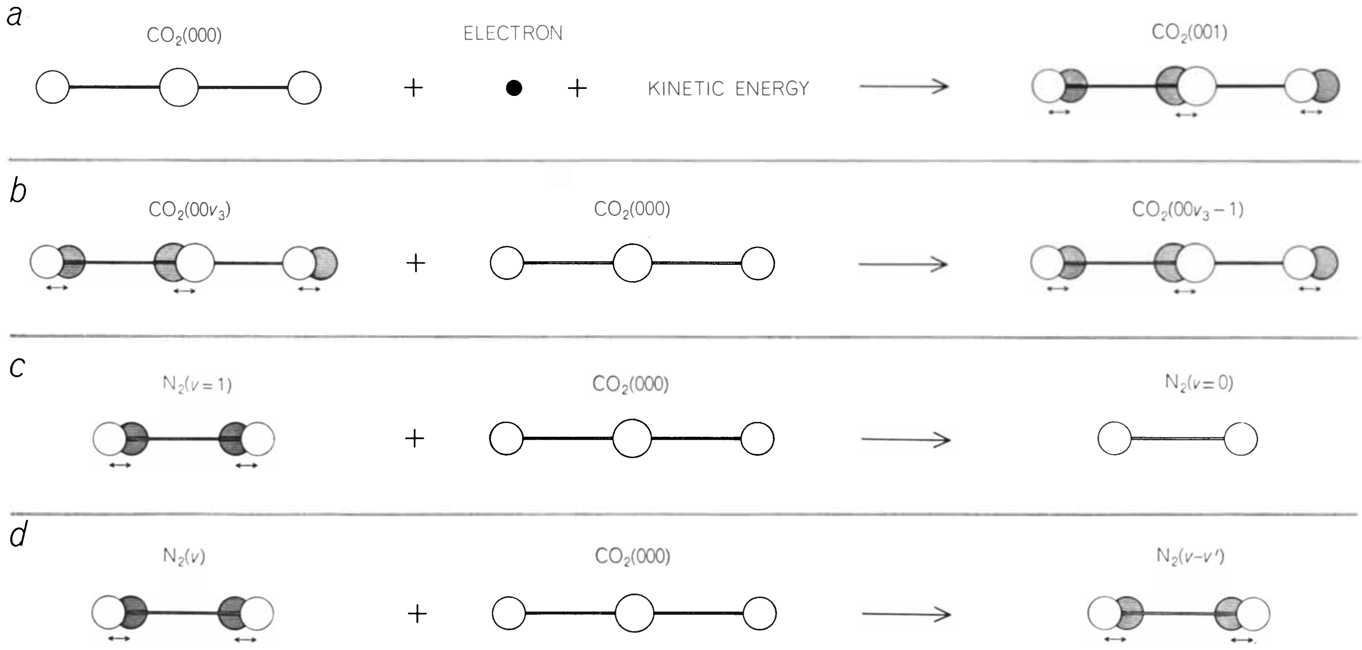
The CO_2(001) molecules can now, for example, emit a laser photon at 10.6 microns and go to the 100 level, from which they have to be returned to ground state before the molecule can be utilized again for producing a laser photon. The molecules at the lower laser level are de-excited essentially through collisions with other molecules. Again the possibility of resonant vibrational energy transfer plays an important role. The lower laser level has nearly twice the energy required to excite the carbon dioxide molecule to the 010 vibrational level. As a result a collision that involves a CO_2(100) or CO_2(020) molecule with a CO_2(000) molecule will efficiently redistribute the vibrational energy between the two molecules by exciting both of them to the CO_2(010) level [*see lower illustration on next two pages*].

Because of the resonant nature of this collision the vibrational de-excitation of the lower laser level is quite efficient. The de-excitation process is not yet complete, however. The CO_2(010) molecules still must be de-excited to the ground state before they can again take part in the laser emission. The de-excitation of CO_2(010) is also governed by collisions, but this time the collisions are nonresonant ones in which the energy of the CO_2(010) molecules has to be converted into kinetic energy. Such collisions can involve other CO_2 molecules, foreign gas particles or the walls of the laser tube.

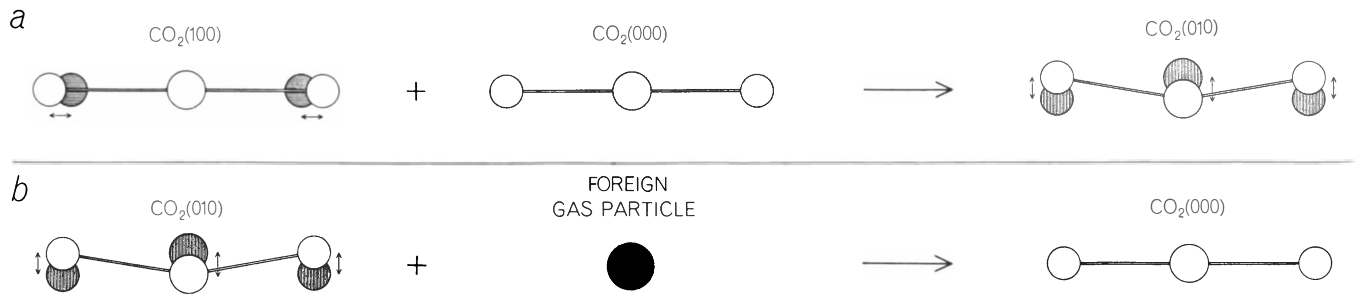
Because of the nonresonant nature of this vibrational energy conversion into kinetic energy the de-excitation of the CO_2(010) molecules can be slow and cause a "bottleneck" in the overall cycle of excitation and de-excitation, thereby reducing the efficiency and the power output. Even for the pure carbon dioxide laser I originally tested, the de-excitation mechanism was sufficiently fast to allow strong laser oscillation on the $001 \rightarrow 100$ and the $001 \rightarrow 020$ vibrational-rotational transitions respectively at 10.6 and 9.6 microns. It was found that because of their larger emission probability the 10.6-micron transitions are stronger than the 9.6-micron transitions by about a factor of 10. For the rest of the article we shall be concerned only with these 10.6-micron transitions.

It is quite clear that electron-impact excitation that occurs in a pure carbon dioxide discharge cannot produce the highly selective excitation of the molecules to the upper laser level that is required for obtaining a practical efficiency approaching the quantum efficiency of the system. The reason is that the electrons can also excite the carbon dioxide molecules to levels other than the $00v_3$ level, causing a reduction in efficiency as well as power output. For high efficiency what is needed is some form of selective excitation of the carbon dioxide molecules to the upper laser level. Such a selective excitation occurs when nitrogen gas is added to the carbon dioxide laser.

The usefulness of nitrogen can be explained by referring to the energy-level diagram of the low-lying vibrational

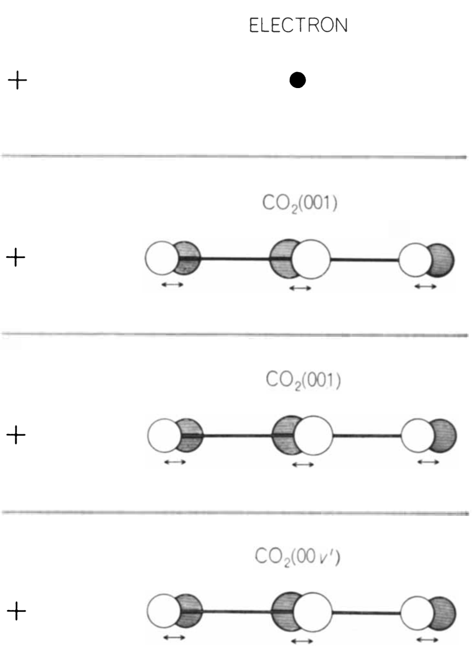


EXCITATION MECHANISMS capable of raising carbon dioxide molecules to the upper laser level (in this case the 001 level) are shown. In an electric discharge the collision of an unexcited, or 000, molecule with an energetic electron can raise the carbon dioxide molecule to the 001 level directly (*a*). Alternatively such a collision can excite the 000 molecule to a $00v_3$ level, where the v_3, or asymmetric stretch, mode has more than one quantum of vibrational energy; in this case subsequent collisions with unexcited molecules result in the transfer of single quanta of vibrational energy to the unexcited molecules, raising them to the 001 level (*b*). In a carbon dioxide–nitrogen laser collisions between vibrationally excited nitrogen molecules and unexcited carbon dioxide molecules

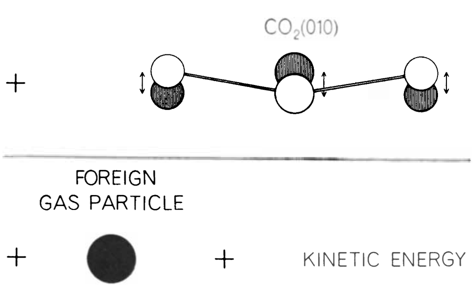


DE-EXCITATION MECHANISMS capable of "depopulating" the lower vibrational levels of carbon dioxide can result in an increased laser power. Two such de-exciting collisions are shown here. In *a* the collision of an excited 100 molecule with an unexcited 000 molecule leaves both molecules at the 010 level. In *b* a molecule at the 010 level can in turn collide with foreign gas particles levels of the electronic ground state of molecular nitrogen [*see illustration on page 27*]. Since nitrogen is a diatomic molecule, it has only one degree of vibrational freedom; its vibrational energy levels are described by quanta of energy arising from vibrations along the internuclear axis alone. Accordingly one vibrational quantum number completely describes the vibrational levels of the nitrogen molecule. Because nitrogen is a homonuclear, diatomic molecule, molecular nitrogen excited to various vibrational levels of the electronic ground state cannot decay radiatively or through collisions, and it is therefore extremely long-lived.

Nitrogen molecules are efficiently ex-



can raise the carbon dioxide molecules to the 001 level by transferring one quantum of vibrational energy from the nitrogen molecule, which can have initially either one (*c*) or more than one (*d*) quanta of vibrational energy going into the collision.



(or with the walls of the laser tube) and thereby return to the ground state, where it is available to be excited once again.

cited from the $v = 0$ level to various higher vibrational levels primarily by electron impact; they can also be excited by cascading from higher electronic states and by the recombination of dissociated nitrogen atoms. In a low-pressure nitrogen discharge one can excite approximately 30 percent of the nitrogen molecules to the $v = 1$ level. Since the energy of excitation of the $N_2(v = 1)$ molecule nearly equals the energy of excitation of the $CO_2(001)$ molecule, one would expect an efficient transfer of vibrational energy from the nitrogen to the carbon dioxide in collisions between the $N_2(v = 1)$ molecule and the $CO_2(000)$ molecule. In such a collision the nitrogen molecule returns from the $v = 1$ level to its ground state by losing one quantum of its vibrational energy and the carbon dioxide molecule is excited from its ground state to the 001 level. Because of the resonant nature of this collision process, the selective excitation of carbon dioxide molecules to the upper laser level should be very efficient.

Furthermore, the higher vibrational levels of the nitrogen molecule are nearly equally spaced, as are the $CO_2(00v_3)$ levels. Hence, in collisions involving $N_2(v)$ and $CO_2(000)$ molecules efficient vibrational energy transfer can take place in which the excited $N_2(v)$ molecule loses v' quanta of vibrational energy and is de-excited to the $N_2(v - v')$ level while the $CO_2(000)$ molecule gains the v' quanta of vibrational energy and is selectively excited to the $CO_2(00v_3 = v')$ level. Since the spacing between the energy levels of the $N_2(v)$ ladder and the $CO_2(00v_3)$ ladder is nearly equal, these collisions involve resonant vibrational energy transfer and the process is very efficient. The $CO_2(00v_3 = v')$ molecules are then converted into $CO_2(001)$ molecules (that is, into the upper-laser-level molecules) through the resonant collisions discussed earlier. In the end one has efficient selective excitation of carbon dioxide molecules to the upper laser level, and one should expect a significant increase in efficiency and power output from a carbon dioxide–nitrogen laser as compared with a pure carbon dioxide laser.

The first experiments to verify this hypothesis were carried out in the system shown on page 32. The gases in the system are continuously flowing. There is no electric discharge in the interaction region, where the laser action is expected to take place. Nitrogen enters through one port and passes through the excitation region, where an electric discharge is produced by means of an oscillating electric field or a high-voltage direct current. The nitrogen molecules are excited to various vibrational levels of the electronic ground state as the nitrogen passes through the discharge region.

Since this is a continuous-flow system, the nitrogen molecules that have been subjected to the discharge are pumped into the interaction region in times that are short compared with the average lifetime of a vibrationally excited nitrogen molecule. Hence the nitrogen gas entering the interaction region will contain a significant fraction of nitrogen molecules that are still excited and that remain in the vibrationally excited levels of the electronic ground state. Carbon dioxide entering through another port mixes with the nitrogen coming through its port. As described above, vibrational energy transfer from nitrogen to carbon dioxide results because of the collisions involving the vibrationally excited nitrogen molecules and the ground-state carbon dioxide molecules. Carbon dioxide molecules are thus selectively excited to the upper laser level. Notice that there is no other form of excitation in the interaction region for exciting the carbon dioxide.

Strong laser oscillation can be obtained in this system on the vibrational-rotational transitions of carbon dioxide even though no discharge is present in the interaction region. After the carbon dioxide molecules have contributed to laser oscillation the continuous-flow system pumps out all the de-excited molecules, and fresh nitrogen discharge products and carbon dioxide enter to continue the laser oscillation. The strength of the laser oscillation proved the effectiveness of using vibrationally excited nitrogen molecules for selective excitation of carbon dioxide molecules to the upper laser level. By mixing nitrogen and carbon dioxide together in a laser tube, with the discharge in the laser region, conversion efficiencies as high as 5 percent have been demonstrated.

Increasing de-excitation of the lower laser levels by removing the "bottleneck" at the 010 level of carbon dioxide can also result in increased power output as well as higher efficiency from the carbon dioxide laser. Earlier I mentioned that de-excitation of the $CO_2(010)$ molecules takes place by conversion of the energy of the $CO_2(010)$ molecule into kinetic energy during a collision with another particle. The rate at which this de-excitation process proceeds depends on the nature of the other particle. For example, carbon dioxide itself has about 100 de-exciting collisions per second at a pressure of one torr, whereas helium atoms have some 4,000 (and water molecules some 100,000) de-exciting transitions per second at the same pressure. Thus we have another method for increasing the power output and efficiency of the nitrogen–carbon dioxide laser system.

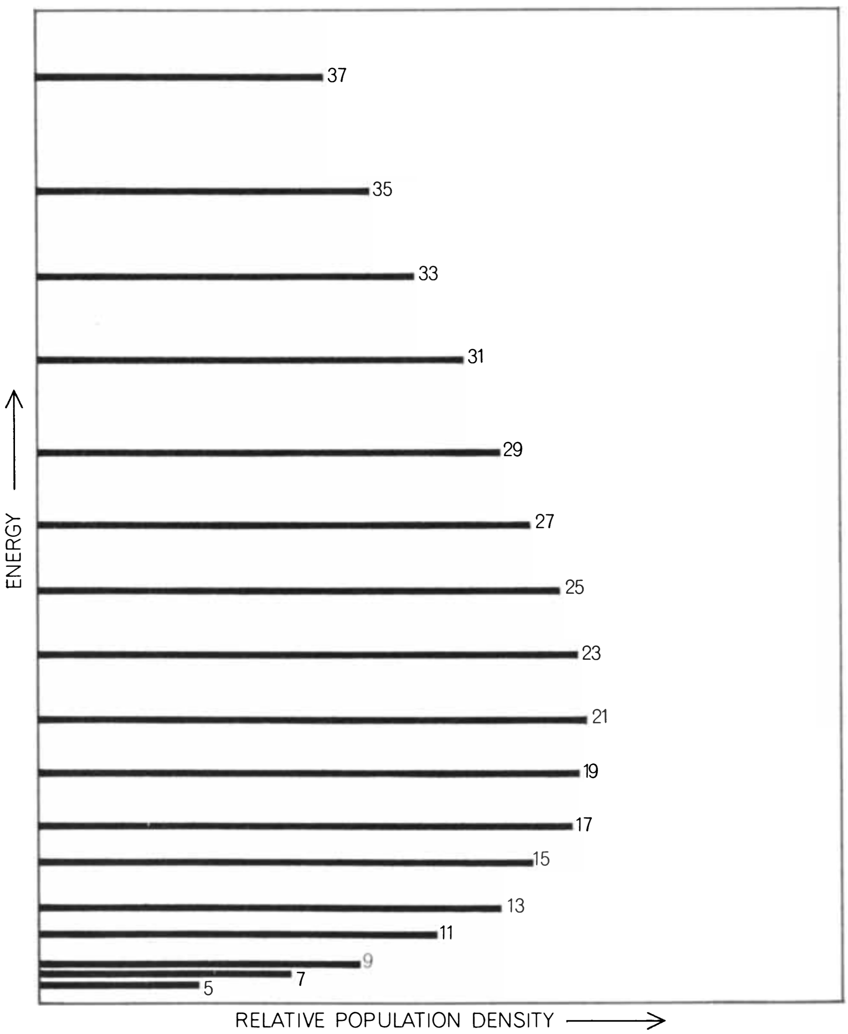
It was found that in order to obtain an extremely high continuous power output at a high efficiency it is necessary to use additional gases in the discharge tube. Gases such as oxygen, water vapor, hydrogen and helium give rise to increased power output. The increase is understood in terms of two effects: (1) the increased rate of de-excitation of the lower vibrational levels of the carbon dioxide molecules and (2) the increase in the rate at which carbon dioxide molecules are excited to the 001 level, either directly by electron-impact processes or indirectly by increasing the excitation rate of the vibrationally excited nitrogen molecules. Both processes for increasing the excitation of the carbon dioxide molecules to the upper laser level are likely if the density of electrons in the discharge is increased and also if the energy distribution of the electrons changes to make it more favorable for exciting the carbon dioxide molecules to the 001 level directly and for faster production of $N_2(v)$ molecules.

Helium seems to be important on both counts and is the most widely used third gas. Water vapor and hydrogen are useful only in terms of the first effect. Carbon monoxide seems to be important from both the excitation and the de-excitation points of view. Using a carbon dioxide pressure of three torr, a nitrogen pressure of three torr and a helium pressure of about 20 torr, a continuous-wave power of some 80 watts per meter of discharge length has been obtained at a wavelength of 10.6 microns. The working efficiency in this case is in excess of 20 percent.

At present most of the high-power carbon dioxide lasers have the gases flowing at a slow rate through the laser tube. Some of our early experiments at the Bell Laboratories and more recent experiments at the Philips Research Laboratory in the Netherlands have shown, however, that it is possible to make sealed-off carbon dioxide lasers if sufficient care is taken in preparing the tube and if the proper gas mixtures are used. These lasers are capable of producing just as much power output as the flowing-gas systems, and the efficiency is quite comparable.

Typical carbon dioxide lasers are about two meters long and can produce continuous-wave laser power of about 150 watts. There is nothing to prevent one from making a very long laser in order to obtain much higher power outputs, since the power output increases linearly with length. In fact, workers at the Raytheon Company have constructed a "folded" carbon dioxide laser that is 600 feet long. This laser has produced continuous-wave power as high as 8.8 kilowatts. The power output of the laser has thus finally caught up with the fantasies of science fiction, and the thermal effects of such output are certainly awesome.

The experimental setup shown in the illustration on page 32 is useful in studying laser action in molecular gases that are unstable, that is, gases that dissociate easily under direct-discharge excitation and/or require an extremely selective excitation for continuous laser operation (for example the diatomic gases). The advantage here is that there is no discharge in the laser region and thus the only levels of the active gas that can be excited are those whose energy coincides with the vibrationally excited nitrogen molecules. In this way continuous laser oscillation was achieved on vibrational-rotational transitions of carbon monoxide (CO) at five to six microns, in nitrous oxide (N_2O) on the 001 → 100 transitions near 10.8 microns and in carbon disulfide (CS_2) on the 021 → 120 transitions near 11 microns.

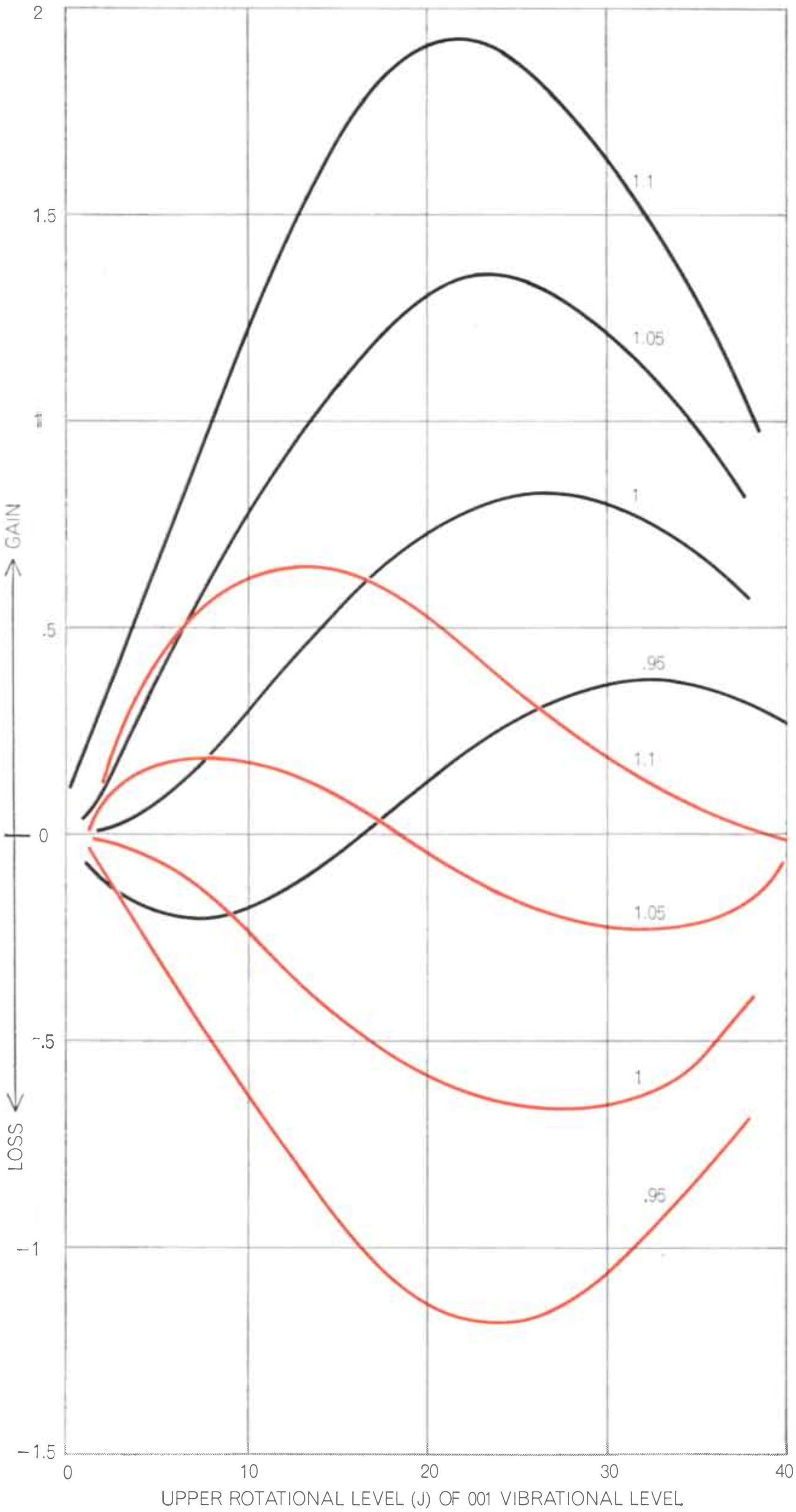


BOLTZMANN DISTRIBUTION of the population densities of the rotational energy levels of the 001 vibrational level of carbon dioxide results from the fact that during its lifetime in a given vibrational level a molecule undergoes a large number of rotational thermalizing collisions, hopping around from one rotational level to another about 10 million times per second. The horizontal scale shows the population densities of the rotational levels at about 400 degrees Kelvin. Vertical energy scale shows the position of each rotational level.

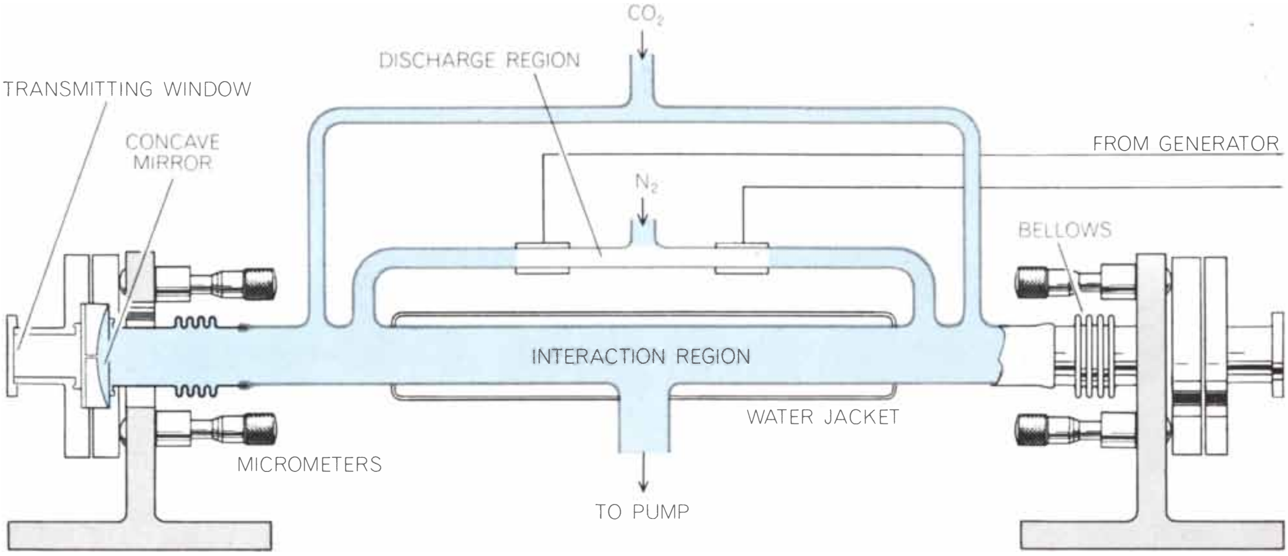
The carbon monoxide laser is particularly interesting from the spectroscopic point of view. We are now able to observe transitions among vibrational levels as high as $v = 25$ in the electronic ground state—transitions that have never been observed before. Nitrous oxide, which is similar in its vibrational modes to carbon dioxide, has the capability of generating high continuous-wave power at an efficiency comparable to that of the carbon dioxide system; it has not, however, been investigated in detail as yet. In any case, the technique of selective excitation for obtaining high power output and high efficiency appears to be generally applicable.

Other techniques for obtaining vibrational excitations in molecules include chemical reactions, heating of gases by flames or burners and optical excitation by matching optical radiation obtained from discharge or flames. These other means have not yet been exploited to any great extent but they do hold promise. The fact that the discharge excitation of the carbon dioxide laser is capable of a conversion efficiency of more than 20 percent, however, poses a formidable challenge to new techniques in terms of practical applications.

So far I have described the mechanisms of excitation and de-excitation that result in the extremely high power output of carbon dioxide lasers, but I have said nothing about the spectrum of the power output. As I have mentioned, the transitions between two vibrational levels occur in the form of a band consisting of P and R branches, because of the closely spaced rotational levels of both the upper and the lower laser vibrational levels. Does this imply that the power output from the carbon dioxide laser occurs at a number of frequencies corresponding to the discrete P-branch and R-branch transitions simultaneously? If the power output were to occur at a number of frequencies, the laser beam would not be truly monochromatic and its usefulness in areas such as communications would be limited. In reality the power output from a high-power carbon dioxide laser can usually be made to occur on a single P-branch transition, usually $P(20)$ at 10.5915 microns, without any trouble, in spite of the fact that the $001 \rightarrow 100$ vibrational band contains a number of possible P-branch and R-branch transitions. This is accomplished by exploiting some rather subtle "competition effects" that take place between the P-branch and the R-branch transitions—a stratagem that in-



COMPETITION EFFECTS among the various possible vibrational-rotational laser transitions of carbon dioxide usually result in one P-branch transition dominating. This set of curves shows the amount of gain (or loss) on a number of P-branch transitions (*color*) and R-branch transitions (*black*) of a given vibrational band. The number associated with each curve gives the ratio of the total population density in the upper, or 001, vibrational laser level to the total population density in the lower, or 100, vibrational laser level.



CONTINUOUS-FLOW SYSTEM was used by the author to verify the hypothesis that a carbon dioxide–nitrogen laser would be more efficient than a pure carbon dioxide laser. Strong laser oscillation was obtained in this system on the vibrational-rotational transitions of carbon dioxide even though no electric discharge was present in the interaction region, thereby proving the effectiveness of using vibrationally excited nitrogen molecules for selective excitation of carbon dioxide molecules to the upper laser level.

creases the usefulness of the carbon dioxide laser tremendously.

It is important to observe that the energy spacings between the various vibrational levels are usually much greater than the kinetic energy of the molecules (which is on the order of .025 electron volt at room temperature). The spacing of the rotational energy levels, on the other hand, is smaller than the kinetic energy. Thus the population density of a particular rotational level in a given vibrational level is not independent of the population density of other rotational levels, since every single collision can result in an exchange of energy equal to the rotational-level spacings. As a result the molecule can jump around from one rotational level to another very frequently. The frequency of this hopping around (also known as the rotational thermalization rate) is in excess of 10 million hops per second for the gas pressures at which the lasers operate. Since the spacing of the vibrational energy levels is much larger than the kinetic energy of the molecules, however, the vibrational thermalization rate is very small: about 1,000 per second. The vibrational-level lifetime, including radiative and collisional relaxation, is about a millisecond whereas the rotational thermalization time is considerably shorter: about 10^{-7} second. This implies that during its lifetime in a vibrational level a molecule undergoes a very large number of rotational thermalizing collisions. This gives rise to a Boltzmann distribution of the molecules among the various rotational levels of a vibrational level [*see illustration on page 30*].

Under the above conditions governing the population densities of the rotational levels one can calculate the amount of gain (or loss) on the various *P*-branch and *R*-branch transitions of a given vibrational band [*see illustration on preceding page*]. From such a calculated set of curves the following useful conclusions can be easily reached: (1) Some *P*-branch transitions show gain even when the total vibrational population density in the lower laser level exceeds that in the upper level. This situation is called "partial inversion," since the *R*-branch transitions do not show gain. (2) When the total vibrational population density in the upper laser level exceeds that in the lower laser level, both *P*-branch and *R*-branch transitions show gain. This is called "complete inversion." (3) Even for the case of complete inversion, an *R*-branch transition always has less gain than a *P*-branch transition starting from the same upper rotational level.

Let us now see what practical effects one can observe from the above conclusions. While it is true that gain occurs on a large number of transitions simultaneously, the existence of a Boltzmann distribution requires that the change of population density of one rotational level affect the population density of all rotational levels in order to maintain the Boltzmann distribution. The rotational transition with the highest gain—in this case transition $P(22)$—will start oscillating first. This will be the strongest *P*-branch transition, since the *R*-branch transitions have lower gain. When this occurs, the rate at which molecules are removed from the $J = 21$ rotational level increases because of the stimulated emission on the $P(22)$ transition. But the requirement of the Boltzmann distribution will result in a transfer of molecules from other rotational levels to the $J = 21$ level and the population density of all the rotational levels decreases even though the laser oscillation on $P(22)$ drains the molecules from the $J = 21$ level. This results in a very strong competition among the possible laser transitions and usually one *P*-branch transition dominates.

As a result of our newfound mastery of these competition effects, the power output from a high-power continuous-wave carbon dioxide laser can be made to occur on a single rotational transition of the $001 \rightarrow 100$ band, thereby ensuring that the high-power output is both extremely coherent and extremely monochromatic.

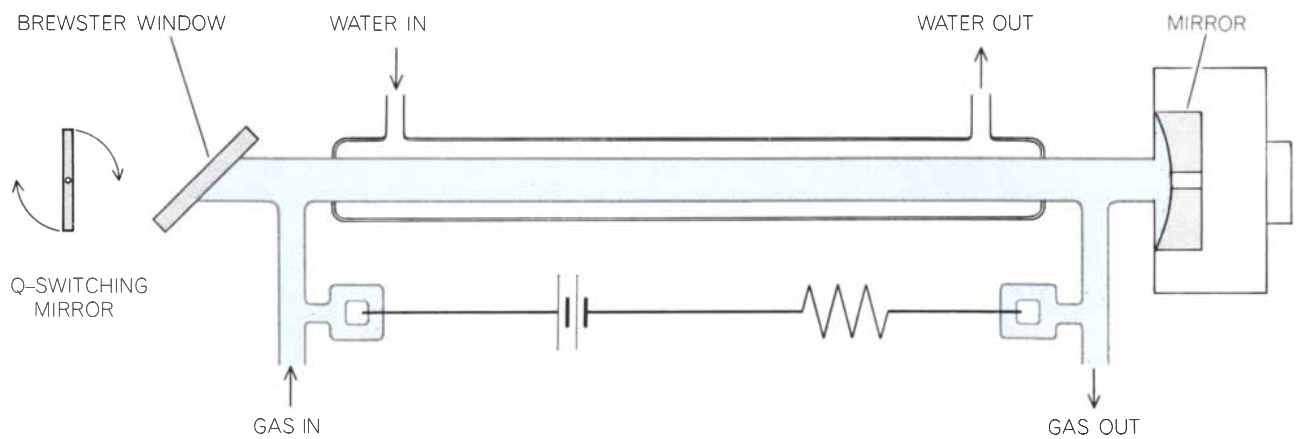
Oscillation is possible on the weaker *P*-branch or *R*-branch transitions provided there is sufficient gain and a wavelength-selecting element such as a grating or a prism is introduced in the laser cavity to prevent the stronger transition from oscillating. Because of the strong competition, one obtains nearly the same amount of power output on any transition that one selects for oscillation, using the wavelength-selecting device.

In addition, because of the long lifetime of the vibrational levels responsible for laser oscillation in carbon dioxide, we can store energy in the discharge medium for about a millisecond by blocking the path of the laser beam within the resonator and thereby preventing the laser oscillation. If the block is suddenly removed, then the output from the laser occurs in the form of a sharp pulse whose peak power is usually 1,000 times larger than the average continuous-wave power obtainable from this laser. This mode of operation is called *Q*-switching. The *Q*-switching is most easily accomplished by replacing one of the laser-cavity mirrors with a rotating mirror [*see illustration below*]. The laser operates every time the rotating mirror lines up with the opposite stationary mirror, putting out an infrared pulse at 10.6 microns. With such a *Q*-switching scheme a carbon dioxide laser capable of producing approximately 50 watts of continuous-wave power will produce nearly 50 kilowatts of pulsed power in bursts approximately 150 nanoseconds long and at a rate of about 400 bursts per second. Such high pulsed-power output with the coherency afforded by gas lasers is particularly useful in nondestructive physical investigations.

An ideal source of coherent radiation is one that can be continuously "tuned," that is, one whose frequency can be changed and controlled continuously. Tuning a high-power molecular laser is not strictly possible, but the number of discrete vibrational-rotational transitions that can be made to oscillate is extremely large. For example, in carbon monoxide alone there are about 200 transitions that oscillate between five and six microns; in carbon dioxide about 100 transitions with high-power output can be made to oscillate between nine and 11 microns. In short, the high-power molecular lasers, although not continuously tunable, offer a wide range of discrete wavelengths at which one can work.

The high continuous-wave and *Q*-switched power made available by the carbon dioxide lasers has many applications. Focusing the coherent infrared output into an area of approximately a thousandth of a square centimeter can give an intensity of a million watts per square centimeter for a continuous-wave laser and an intensity of a billion watts per square centimeter for a *Q*-switched laser. Continuous-wave powers in excess of one kilowatt have obvious thermal applications such as metal cutting and welding. A strange "softening" of granite rock is also reported when the rock is irradiated with a kilowatt of power from a carbon dioxide laser. The output from the carbon dioxide laser at 10.6 microns, although invisible to the eye, is just as devastating as that from any other powerful laser. The thermal applications of the carbon dioxide lasers command considerable industrial interest.

More important, however, are the nonthermal applications of the carbon dioxide laser. These potential applications include optical communications both on the earth and in space. The main attraction here is the low-loss optical "window" that exists between eight and 14 microns for transmission through the earth's atmosphere. The high efficiency and high power of the carbon dioxide lasers at 10.6 microns make them ideal candidates for such applications. The carbon dioxide laser is also ideal for use in optical radar systems, again because of low-loss transmission through the atmosphere. Another possibility is the use of a carbon dioxide laser to investigate optical interactions with matter at a wavelength of 10.6 microns, since many semiconductors that are opaque in the visible portion of the spectrum are transparent at this wavelength. Still another application of the high-power carbon dioxide laser is the use of the 10.6-micron radiation as a "pump" for studying nonlinear properties of new materials with the aim of making a really tunable source of infrared radiation. In this connection my colleagues and I have performed a number of interesting experiments, which include second-harmonic generation, parametric amplification of far-infrared radiation, two-photon electron-hole pair production in semiconductors, nonlinearities arising from conduction electrons in semiconductors and Raman scattering from Landau-level electrons in semiconductors. Some of these mechanisms are strong enough to enable us to make a tunable laser oscillator in the infrared portion of the spectrum. Such a tunable laser, pumped with the fixed-frequency carbon dioxide laser, can be used as a local oscillator in an optical communication or radar system. Moreover, such a tunable infrared source would completely revolutionize infrared spectroscopy. The description of these experiments will perhaps be the subject of a future article. In conclusion, it suffices to say that the carbon dioxide lasers have already opened up avenues of physical investigation undreamed of before, and they promise many more fruitful experiments in the future.



***Q*-SWITCHING, a technique for operating a normally continuous-wave laser in a pulsed mode, is accomplished by replacing one of the laser-cavity mirrors with a rotating mirror. The laser operates every time the rotating mirror (*left*) lines up with the opposite stationary mirror (*right*). A carbon dioxide laser capable of producing approximately 50 watts of continuous-wave power will produce nearly 50 kilowatts of *Q*-switched power in bursts approximately 150 nanoseconds long and at a rate of about 400 bursts per second.**

L-ASPARAGINE AND LEUKEMIA

The cells of some leukemias need an outside supply of the amino acid L-asparagine. This means they are vulnerable to treatment with the enzyme L-asparaginase, which destroys the amino acid

by Lloyd J. Old, Edward A. Boyse and H. A. Campbell

Cancer presents a special challenge to the investigator, not only as a hazard to life and health but also as a problem in the fundamental processes of living organisms. Intensive efforts have been made to find substances capable of destroying cancer cells selectively, and useful compounds have been discovered that will prolong the survival of cancer patients. These chemotherapeutic compounds have the deficiency that their lethal action is not confined to cancer cells: it extends in various degrees to normal cells. Their use is therefore limited by their toxicity for normal cells, particularly for cells with a high rate of multiplication, such as the cells of the blood-forming tissues and those of the intestinal lining.

The main reason for this relative lack of success is past failure to detect any absolute biochemical property that distinguishes a cancer cell from a comparable normal cell. For years cancer investigators have been looking for substances made only by cancer cells or required only by cancer cells, because such substances would offer a point of attack specifically against the cancer cell. Among the most significant developments of the past few years is the demonstration that cancer cells do indeed differ from normal cells, both in structure and in metabolism.

The evidence for differences in structure has come from studies in immunology. Components unknown in normal cells, recognizable by immunological methods as antigens, have been found in malignant cells, and this is probably characteristic of all types of cancer to which experimental animals are susceptible. Research in this area now includes ways to exploit the newfound antigenic differences, with the long-range goal of controlling cancer by immunization.

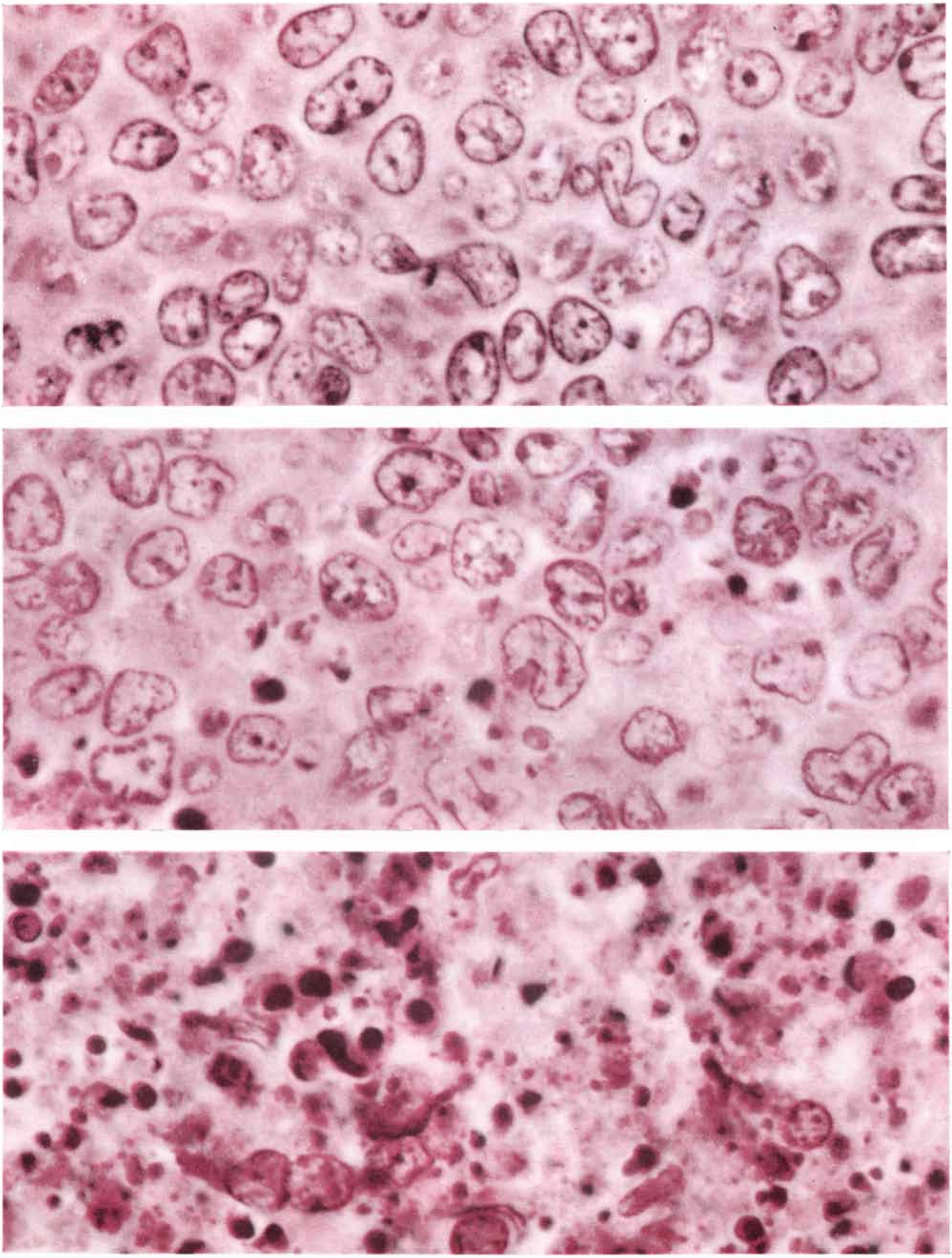
The work we shall review here is concerned more with metabolic differences than with structural ones. Evidence that the metabolism of cancer cells differs significantly from the metabolism of normal cells has been sought for some time, but only recently has such a distinction come to light. As a result of experiments undertaken in the 1950's it is now known that if malignant cells of certain types are deprived of asparagine, a common amino acid that normal cells apparently can synthesize for themselves, they die. The discovery of this metabolic defect of some malignant cells, and the recognition that it can be exploited in the treatment of cancer, is one of the landmarks of modern cancer research. We shall trace the history of this discovery and report on the prospects for its clinical application.

In 1953 John G. Kidd of the Cornell University Medical College reported experiments originally concerned with immunological responses to cancer. He wanted to see if antiserum taken from rabbits immunized with a transplanted mouse leukemia would affect the growth of the leukemia in mice. Here it should be explained that animal leukemias are maintained for study in the laboratory by transplanting the malignant cells from one animal to another; there they continue to proliferate, rendering the new host leukemic and providing more cells for subsequent transplantation. In general this is possible only because the animals used for the purpose have been inbred for many generations to the point of genetic uniformity. They no longer reject grafts of one another's tissues and consequently accept serially grafted leukemias and other cancers arising in the same inbred strain.

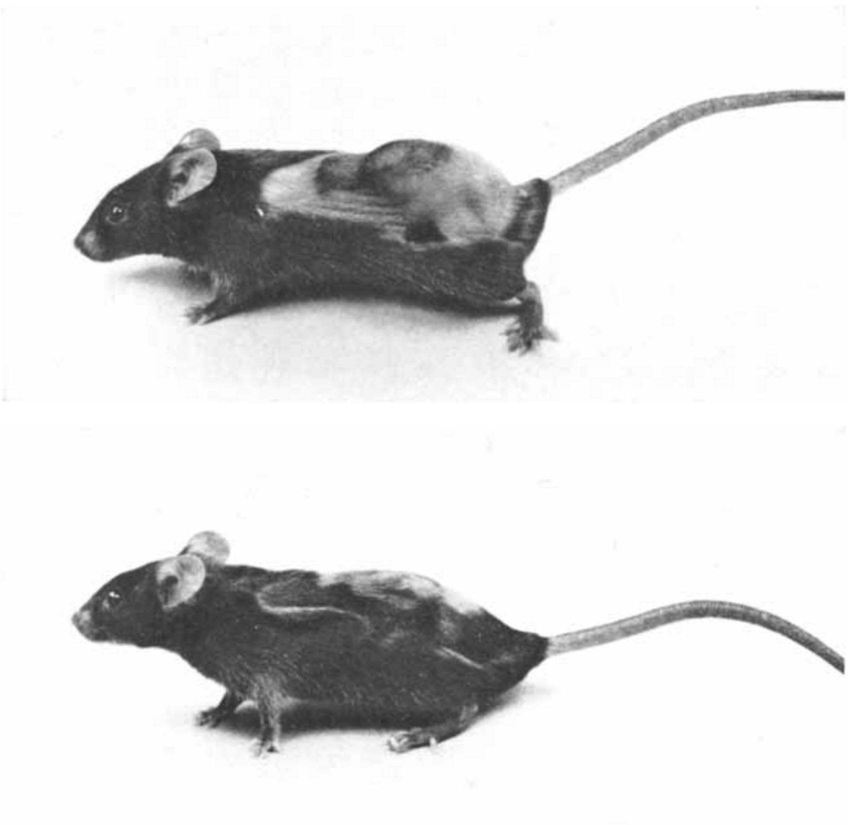
After transplanting a leukemia into a group of mice, Kidd gave the mice injections of the rabbit antiserum and also injections of serum taken from healthy guinea pigs. Guinea-pig serum is rich in certain proteins, known collectively as "complement," that augment antibody reactions. The guinea-pig serum was injected with the aim of increasing the effectiveness of any antibodies present in the rabbit serum.

As an experimental control Kidd also injected some leukemic mice with guinea-pig serum alone. To his surprise the leukemia of these mice regressed and in some instances disappeared permanently. He went on to establish three important facts concerning what came to be known as the "Kidd phenomenon." First, he showed that guinea-pig serum was the only serum that had this effect on leukemias. (We shall see that this statement was later qualified.) Serum from rabbits, horses and humans produced no response. Second, he established that the guinea-pig serum apparently affected only malignant cells, leaving the mouse's normal tissues unaltered and for this reason producing no toxic side effects. Third, he found that the guinea-pig serum affected some transplanted leukemias but not others. The unaffected group included all the newly transplanted leukemias, which at first made it appear that the only responsive leukemias were those that had had a long history of transplantation.

Not long after Kidd's discovery Thomas A. McCoy and his colleagues at the Samuel Roberts Noble Foundation in Ardmore, Okla., reported the results of a nutritional study of animal cancer cells grown in laboratory culture. Among other observations, McCoy and his associates noted that cultures of certain rat-tumor cells sooner or later die unless they are supplied with L-asparagine. This substance was among the first amino acids to be isolated by the pioneering biochemists of the 19th century; the



DESTRUCTION OF LEUKEMIA CELLS in mice by a single injection of the enzyme L-asparaginase is shown in this series of photomicrographs made at the Sloan-Kettering Institute for Cancer Research. In the micrograph at top is leukemic tissue taken from a mouse before it had received the injection; the round bodies are leukemia cell nuclei. In the middle micrograph is a similar sample taken from a mouse four hours after an injection; the comparatively small dark spots are leukemia cells that have died. In the micrograph at the bottom is a third sample, taken from a mouse 17 hours after an injection; most of the leukemia cells are dead.



HOST MOUSE, its shaved back swollen with a transplanted leukemia (*top*), has received a single injection of L-asparaginase. After seven days (*bottom*) the swelling has disappeared.

prefix *L* indicates that it is in the three-dimensional form designated levorotary. Although asparagine is a constituent of animal proteins, nutritional studies have shown that it is not one of the amino acids essential to an adequate animal diet. It was therefore concluded that normal animal cells can synthesize their own supply of asparagine. Indeed, the studies of several other investigators interested in the amino acid requirements of cells growing in laboratory culture had not revealed any instance in which L-asparagine needed to be added to the culture medium.

The importance of Kidd's and McCoy's findings was not widely appreciated at the time, nor was a connection perceived between them. With respect to Kidd's work the prevailing impression was that his results might in some way depend on the circumstances of prolonged transplantation. Since the leukemias that responded to guinea-pig serum in his experiments had been transplanted a large number of times, they might have become immunologically incompatible with their mouse hosts. The newly transplanted leukemias were not under suspicion of incompatibility and had not responded to the serum. Hence it was commonly supposed that the Kidd phenomenon, although a fascinating puzzle, concerned tissue-transplantation biology rather than cancer.

Several years passed before the two apparently unrelated findings were shown to be two sides of the same coin. John D. Broome, who was then at the Cornell University Medical College, convinced himself that Kidd's results could not be attributed to immunological rejection. Searching for nonimmunological differences between guinea-pig serum and the serum of other animals, Broome found that in the 1920's A. Clementi, an investigator at the University of Rome, had discovered that the blood of guinea pigs contained an enzyme that destroys asparagine. This enzyme was absent from the blood of many other animals he tested. Broome then began experiments that left no doubt that the enzyme of guinea-pig serum, called asparaginase, is the antileukemic factor responsible for the Kidd phenomenon.

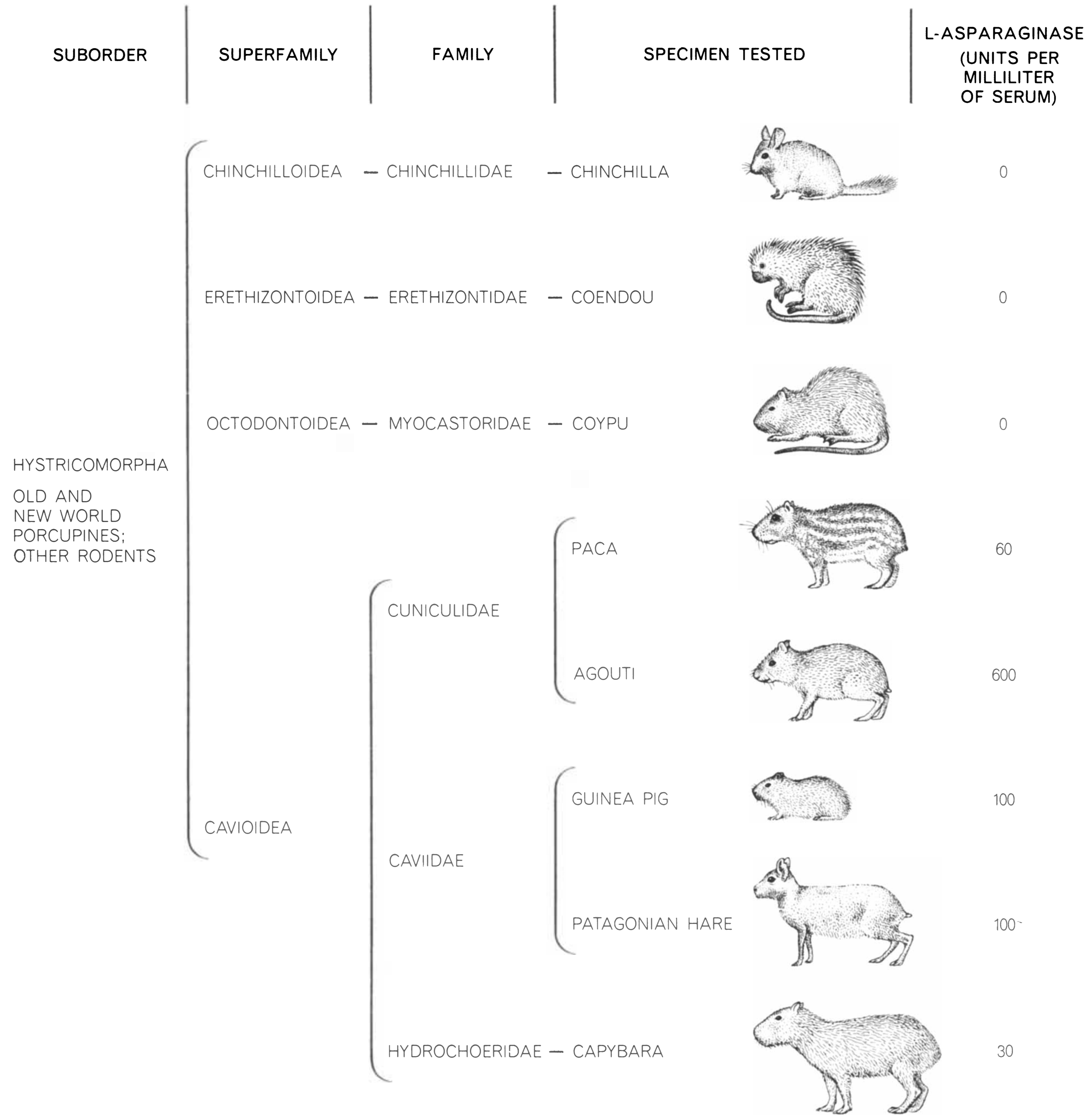
The strength of Broome's conclusions lay in his use of evidence from two independent experimental approaches. With one of the same transplanted leukemias that Kidd had studied, he showed first that the antileukemia property of guinea-pig serum could not be distinguished from asparaginase activity by a variety of physical and chemical methods, indicating that by these criteria they are one and the same. Second, he showed that this type of leukemia needed a supply of L-asparagine in order to grow in culture. In cultures lacking asparagine most of the leukemia cells were dead within a few days, although when these cultures were maintained for several weeks instead of being discarded, the few remaining cells began to grow without asparagine. When these cells were transplanted into mice once again, they no longer responded to guinea-pig serum.

Broome's incisive investigation of the Kidd phenomenon, published in *Nature* in 1961, did not receive immediate and wide recognition. Even today some reviews of cancer biochemistry make little or no mention of it. Major findings frequently go unrecognized, however, because they run contrary to established opinion—in this case the opinion that an absolute distinction between cancer cells and normal cells does not exist.

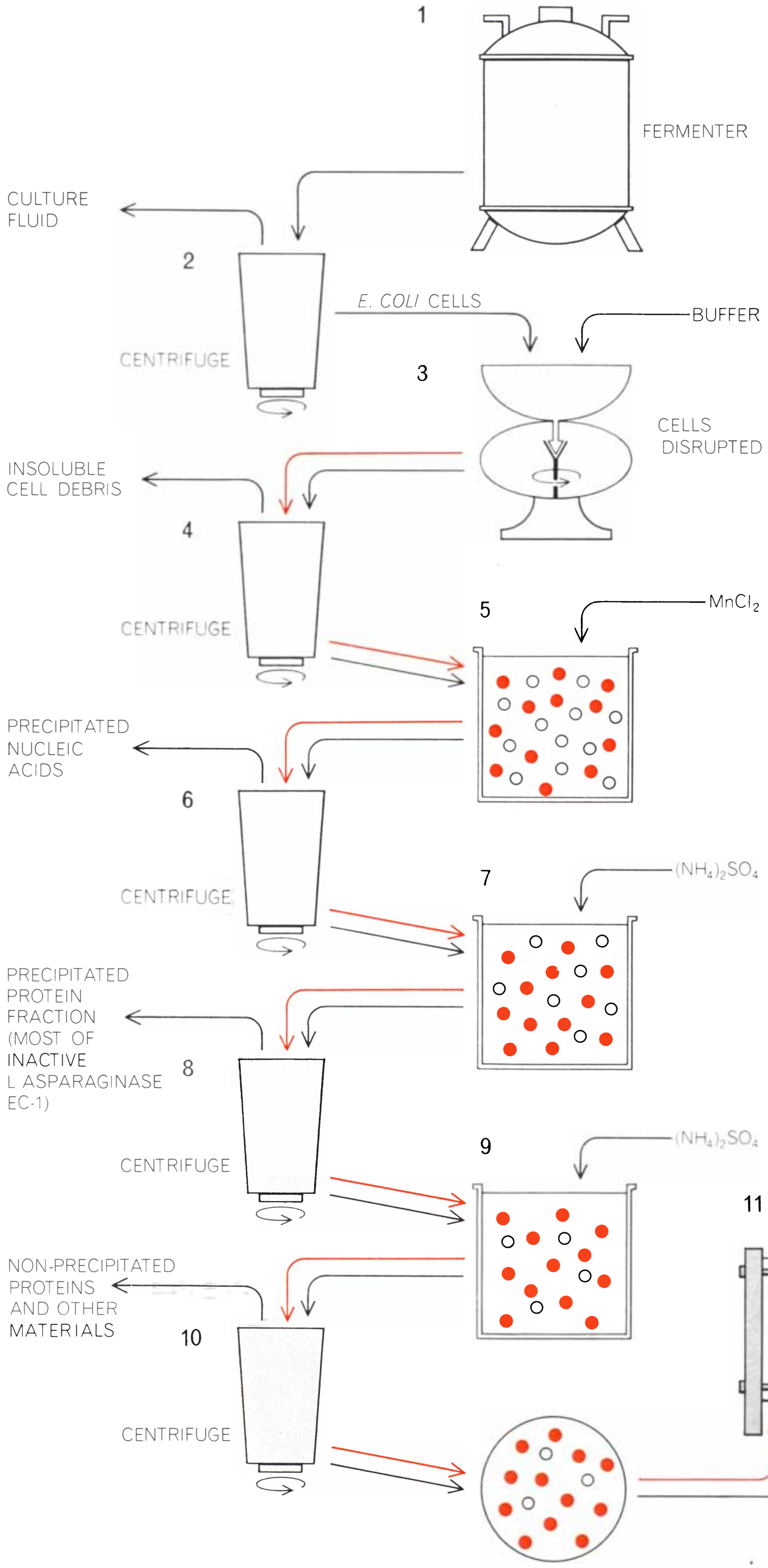
Since 1961 our group at the Sloan-Kettering Institute for Cancer Research has studied more than 100 newly transplanted mouse leukemias. This work has been directed primarily toward elucidating the antigenic structure of these leukemias in relation to their cause. It has shed further light on the Kidd phenomenon, furnishing the reason for the earlier view that only long-transplanted leukemias were affected by guinea-pig serum. First of all, it became evident that asparagine dependence is a common attribute of certain types of mouse leukemia, and that the dependence is unrelated to the transplantation history of particular leukemias. There is, however, a class of mouse leukemias that seldom exhibit dependence on asparagine. This is the class of leukemias caused by the known leukemia viruses of mice. The leukemias Kidd used for testing the effect of guinea-pig serum on new transplants came from strains of mice that carry leukemia virus and are therefore prone to the disease. Such leukemias are the most readily obtainable, but they belong, as we now realize, to an unresponsive class.

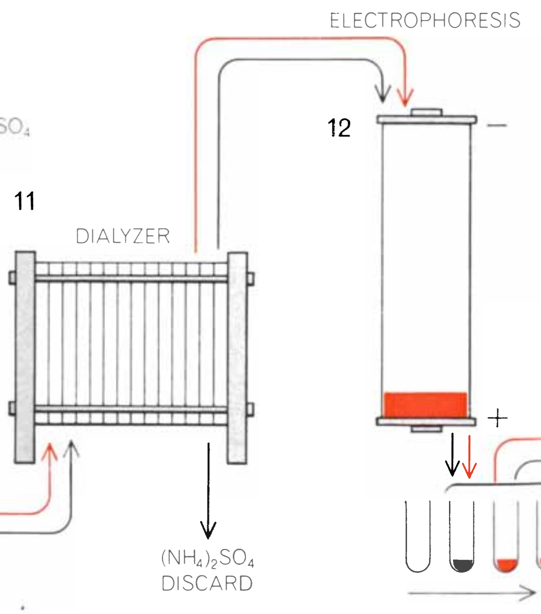
At this point the question that came to the fore was: Is responsiveness to asparaginase a peculiarity of certain rodent leukemias, or is it characteristic of cancer in many species? Before we could readily seek an answer we needed a source of asparaginase more plentiful than the guinea pig could provide. The guinea pig belongs to a superfamily of South American rodents, the Cavioidea; this superfamily includes the capybara (the largest of all rodents), the Patagonian hare, the paca and the agouti (all substantially larger than the guinea pig). Serums from a number of South American rodents have been tested by us and by Nelson D. Holmquist of the Louisiana State University School of Medicine. L-asparaginase activity has been found in the serum of all the members of the superfamily Cavioidea. As expected, the presence of L-asparaginase confers on these serums the ability to suppress leukemias that are known to respond to guinea-pig serum. In agouti serum the enzyme was six times as abundant as it is in guinea-pig serum. Serum from more distant relatives of the guinea pig—members of different superfamilies in the same suborder—did not contain asparaginase, showing that the occurrence of asparaginase in blood is a phylogenetic character dating back to a period before the evolutionary diversification of the Cavioidea.

Asparaginase is found in many cells of animals and plants. The Cavioidea are unusual only in that the enzyme is released from the cells and circulates in the blood serum. It seemed that the problem of supply might best be solved by extracting an effective asparaginase from microorganisms, but early attempts to accomplish this were not successful. For a time it appeared that the agouti might be the most feasible source of the enzyme in quantity. In fact, a patient was treated with agouti serum in 1965 by a group of physicians at the University of Recife in Brazil. Then Louise T. Mashburn and John C. Wriston, Jr., of the University of Delaware found that an asparaginase that was effective against



SOUTH AMERICAN RODENTS of the suborder Hystricomorpha include five whose blood contains the enzyme L-asparaginase. Not all rodents in the group share this characteristic; the authors have not detected the enzyme in chinchilla, coendou or coypu blood.





mouse leukemia could be extracted from the common colon bacillus *Escherichia coli*. Because *E. coli* can be cultivated in massive quantities it provides a potentially inexhaustible supply of the enzyme.

Asparaginases made by various organisms differ somewhat in structure and properties, although they share the faculty of destroying asparagine. We now realize that not all of them are equally effective in suppressing leukemias. Some may be cleared from the body too rapidly, the conditions in the body may be unfavorable for enzymatic activity in particular instances, and so on. For example, asparaginase from yeast has no activity against leukemia. *E. coli* produces two forms of enzyme, only one of which (EC-2) has antileukemia activity. The inactive form (EC-1) is eliminated in a multistage extraction process [*see illustration on these two pages*].

Therefore the limiting factor was no longer the availability of asparaginase but its extraction and purification. Crude bacterial extracts are highly toxic. Joseph D. Teller of the Worthington Biochemical Corporation had been working on methods for preparing large amounts of *E. coli* asparaginase, and by 1966 he was able to provide enough of the enzyme for its trial in the treatment of lymphosarcoma in dogs. We chose dogs because they belong to an order of mammals (the carnivores) that is far enough removed from the order of rodents to represent a significant test of how general the occurrence of asparagine-dependent cancers

L-ASPARAGINASE CAN BE OBTAINED from bacteria rather than from animals by the process outlined here. The bacterium is the common colon bacillus *Escherichia coli*. The bacteria are first grown in a fermenter (*1*). Then the culture fluid is removed (*2*)

is. Moreover, dogs have a high frequency of lymphosarcoma, which resembles some human cancers. In our first experiments (undertaken with Robert S. Brodey and I. J. Fidler of the University of Pennsylvania School of Veterinary Medicine) we selected three dogs in which the disease was far advanced; the dogs' lymph nodes and tonsils were greatly enlarged and the animals were scarcely able to eat or move about.

The results of treatment with asparaginase were striking. Within a week injections of the enzyme restored two of the dogs to apparently normal health, and the third dog showed considerable improvement. It is remarkable that cancerous tissue can be destroyed on such a scale, with the concomitant release of breakdown products, without evidence of toxicity.

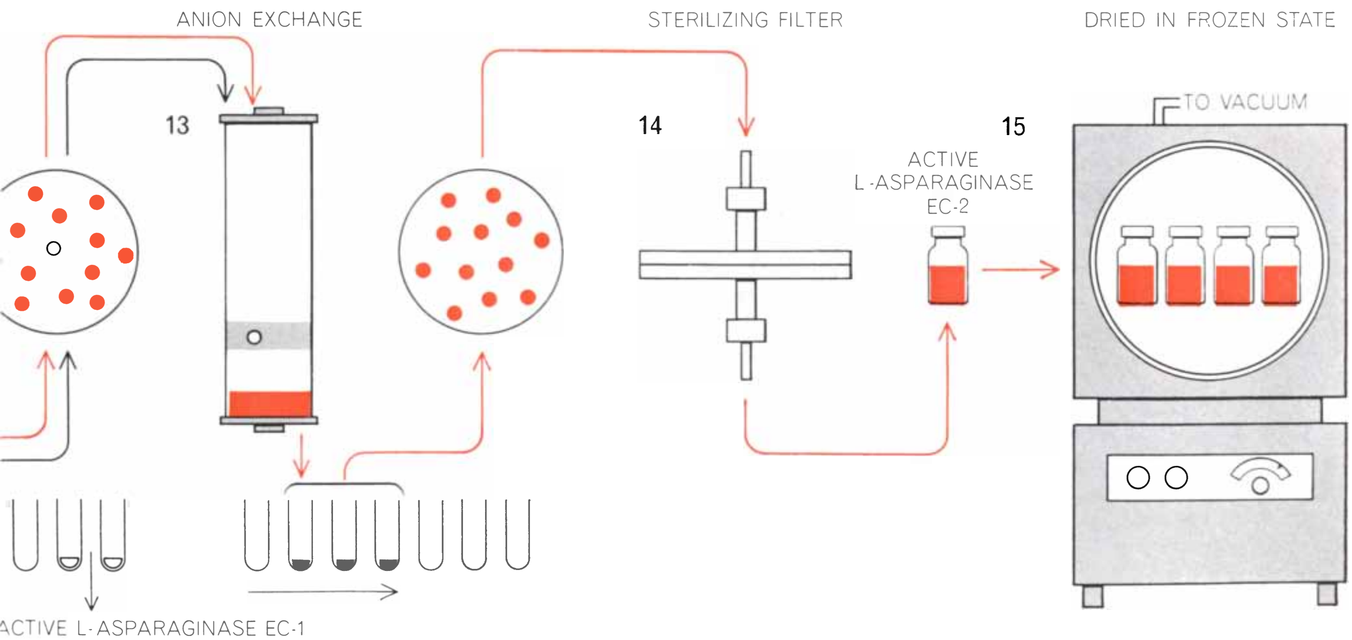
Because asparaginase was still comparatively scarce we were not able to test the effects of massive doses or more extended periods of treatment. The lymphosarcoma reappeared in the dogs between seven and 50 days after the injections had been discontinued. Asparaginase was nonetheless available for a second course of treatment for one of the dogs, and the response of the animal was equally striking.

With evidence that asparaginase was effective against cancers of animals as distantly related as mice and dogs, hopes were raised that asparagine deprivation would prove effective in destroying some forms of cancer in man. Clinical studies undertaken last year at the Sloan-Kettering Institute and at the Wadley Institute of Molecular Biology in Dallas have shown that one kind of human leukemia, the acute lymphoblastic type, often exhibits the metabolic defect that makes cancer cells vulnerable to asparaginase. Leukemia in children is commonly of this type. To judge both from laboratory tests with cultured cells and from patients' response to treatment, the majority of such leukemias are asparagine-dependent. It is these leukemias that have been the most intensively studied so far, but there is hope that other types of human leukemia and other human cancers may also be affected by asparaginase.

The degree of benefit to be gained from asparaginase therapy, even with respect to leukemia of the acute lymphoblastic type, remains unknown. Although the enzyme causes gross manifestations of the disease to disappear for various periods of time, it is not the only substance that can accomplish this result. Certain hormones of the adrenal cortex and drugs that interfere with the synthesis of nucleic acid will also induce such remission. The distinction between asparaginase and other agents is that the enzyme has an obvious adverse effect only on malignant cells, whereas the other substances are not inherently selective in their action. Since the action of asparaginase is specific, it should follow that the patient will suffer no side effects attributable to the enzyme alone (as contrasted with those attributable to toxic contaminants). So far the supply of sufficiently pure asparaginase has been too limited to allow even a determination of how much can safely be administered in man. The dosage may well be many times the amount now being used in treatment.

Supplies of asparaginase for clinical use are likely to remain inadequate for some time. For this reason it is desirable to have tests that precede the treatment of patients and can determine in advance whether a particular cancer is asparagine-dependent. Several laboratory tests are possible. Asparagine-dependent cells of mouse leukemias and of dog lymphosarcomas may die so rapidly (within 24 hours) when they are cultured without asparagine that this alone can suffice to distinguish asparagine-requiring leukemias in these animals. Cultures of human leukemia cells, however, do not give equally clear-cut results with this simple test. Nor is the failure of cancer cells to proliferate in the absence of asparagine an adequate test in man, as it is with some transplanted leukemias in mice. The reason is that most primary cancers in man and animals do not multiply the same way in culture.

We therefore resorted to another test (first applied by L. H. Sobin and Kidd in mice) that measures the response of cultured cancer cells to asparagine deprivation. It is based on the fact that living cells continuously synthesize protein and nucleic acid. Cultures of cancer cells, some with asparagine and some without, are therefore incubated with radioactive-



and the bacterial cells are disrupted (3). Next the material other than L-asparaginase EC-2 is removed by a variety of techniques (4 ***through 14*)**, including salt fractionation, electrophoresis, ion exchange and filtration. Finally enzyme is freeze-dried for storage.**

BOSTON TERRIER WITH LYMPHOSARCOMA has massively enlarged glands in the neck. (The neck is shaved.) After photograph was made dog was treated with L-asparaginase.

AFTER 10 DAYS OF TREATMENT the dog was restored to apparently normal health. Treatment was given by W. D. Hardy, Jr., of Sloan-Kettering Institute for Cancer Research.

ly labeled precursors of protein or nucleic acid. If the deprived culture fails to show sustained incorporation of the labeled precursors into newly synthesized protein and nucleic acid, we conclude that the cancer is asparagine-dependent. With mouse leukemias the test shows within as short a period as 30 minutes whether or not the cancer cells are subject to destruction by asparaginase. It is now being widely applied in studying the asparagine requirements of human cancer cells.

Many questions await solution. What types of human cancer, in addition to leukemia, will respond to asparaginase? Asparagine-requiring cancers of other kinds are known in rats and dogs, and it is hoped that the same may be true in man. A leading theoretical question is *why* some cells need an external supply of asparagine. Do they require more asparagine than they can synthesize? Or have they lost the capacity to synthesize the amino acid? Studies in a number of laboratories suggest that the latter is the case. It appears that asparagine-dependent cells lack an enzyme, asparagine synthetase, that in normal cells (and in cancer cells unresponsive to asparaginase) converts aspartic acid to asparagine. This suggests a parallel with microorganisms in which mutation has caused the loss of an enzyme, or the production of a defective enzyme, leading to an absolute requirement for a substance that would normally be synthesized.

The behavior of cancers may suggest that malignant cells revert to a primitive state in which they show decreased dependence on external conditions. This is the impression one gains on observing how a cancer thrives as the body wastes away. It is thus particularly gratifying to find that some cancer cells, rather than attaining metabolic independence, have lost the ability to perform a function of which normal tissues are capable.

The recognition of asparagine dependence as a property of certain cancers helps to stem the tide of pessimism generated by years of biochemical research that did not reveal absolute distinctions that would point the way to specific cancer therapies. There is clearly a possibility that other specific nutritional requirements of cancer cells may come to light, suggesting other enzymes and other approaches that may be of value in the treatment of cancer. The optimistic view is that the defect in asparagine metabolism will prove not to be the only example of its kind.

In hope of doing each other some good

Peanut sprouting

Oil-bearing seeds store energy as fat. To release the energy for the seedling, enzymes must first split off the fatty acid chains from the supporting glyceryl structure.

Those fat-splitting enzymes, the lipases, are a big subject. Many a biochemist devotes his days to detecting, identifying, or measuring lipases.

In recent years we have been able to help a bit by making Fluorescein Dibutyrate for them as EASTMAN 8965. The lipases split it as though it were a real fat. Its fluorescein moiety plays no physically supporting role, as does the glyceryl structure in a seed or in a man's adipose tissue, but serves by fluorescing when set free of its two butyryl radicals and thus signals to the biochemist that a lipase is at work.

Last year T. J. Jacks and H. W. Kircher at the Seed Protein Pioneering Research Laboratory of the U.S. Department of Agriculture in New Orleans reported that the biochemist could get much more lipase sensitivity with a brighter phosphor than fluorescein, namely 4-methylumbelliferone which, without that unmellifluous name, may at one time have been plugged by laundry-detergent makers on their operas as "brightener." It split best from fatty acid chains six to nine carbons long.

The report in *Analytical Biochemistry, 21,* 279 (1967) caught the eye of an M.D. chemist who thinks that there would be much wider use of serum lipase level of the blood and urine as an indicator of pancreatitis if the tests for it were faster and more sensitive. So he wrote to us.

Before Fluorescein Dibutyrate came in, the usual procedure took up to 24 hours of incubation. To our correspondent, what the seed protein people had found looked like a comparable gain over Fluorescein Dibutyrate. He asked us to make him some 4-Methylumbelliferone Butyrate, and we have. Before and after and whether or not he sheds his anonymity by making known his findings on how well it works, other investigators who order it as EASTMAN 10462 can check it out for themselves if it is important to them.

From **B & A / CURTIN / FISHER / HOWE & FRENCH / NORTH-STRONG / SARGENT / VAN WATERS & ROGERS / WALKER / WILL**—*well-known laboratory suppliers all.* EASTMAN *Organic Chemicals List No. 44 and its Cumulative Supplement 44-4 are sent on request by Distillation Products Industries, Rochester, N.Y. 14603.* EASTMAN *10462 is too new to be found therein.*

The competitive spirit updated

As perceived by the young returning next month for their last year on campus or emerging soon from military to civilian life, we are a monolith. Certain ones before long will get a chance to penetrate the illusion. First they will reveal themselves to a recruiter, who will like what he hears and sees. Invitations to Rochester will be issued and accepted. Choices will there be offered. If the recruiter knows his stuff, several divisions will share his enthusiasm for the candidate. No more monolith.

Listen, for example, to Photo Technology Division striving for favor and identity:

"If you come with us, you will soon see how the picture is our product. Other divisions make film base, make emulsions, lay the emulsions down on the base, make paper, make chemicals, make equipment, test all these individual components to their individual specifications. Our concern is to systematize them to give the consumer the ultimate object he has in mind when he lays his money down on the counter—a picture that pleases. We got going only about 20 years ago when businessmen realized that the merchandise itemized on the customer's invoice is only the means for him to get it.

"Now, the customer who wants that picture ought not to have to put himself completely in Kodak's hands unless he finds it best to do so. He ought to be able to pick and choose whom he does business with. Kodak wants the photographic business to be good for all who participate in it. Only highly satisfactory pictures can accomplish that. Therefore our mission here is to apply any concept or device from any branch of engineering or science —or the fine arts—that can contribute to that purpose.

"Anything needed for the finished picture that is chosen from Kodak gives us the chance we want. Any improvements we pack into that product had better interface to the customer's best advantage with the technology of other companies, even though responsibility for performance of their products remains theirs alone.

"So a constant stream of them pours through here all the time. A lot of them offer complicated equipment or services that work behind the scenes and are little known to the guy looking at the final result in his hand, on the wall, or on the screen. Some compete with us and some don't. Some of the creative labor that builds our technology depends for support on patents and some on proprietary secrecy. All of which builds excitement.

"Then, of course, there is this very comfortable new 8-story building we have just expanded into."

Other divisions can make themselves sound just as well balanced between an invigorating tension and a confident relaxation. The recruiters work out of Business and Technical Personnel Department, Eastman Kodak Company, Rochester, N.Y. 14650. No harm in dropping a line at any time.

Counting on the coach

Yes, it is true that in the use of super 8 movies for instruction and analysis, athletic coaches are a major influence.

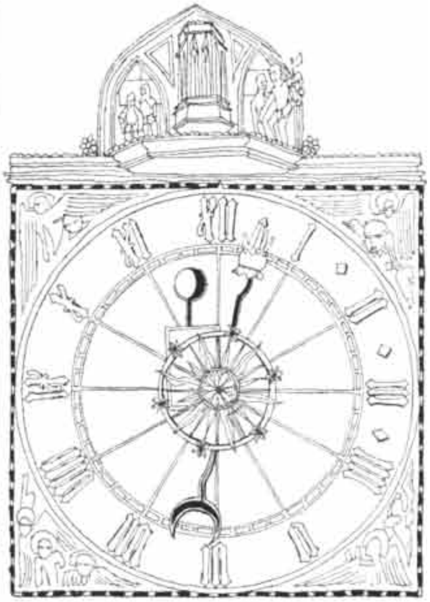
No, we might not have yet marketed the new KODAK EKTAGRAPHIC MFS-8 Projector were it not for them. Coaches enjoy wide support. They will buy this projector.

It can stop by itself at any marked frames on a reel up to 400 feet long, without noticeable change in focus or brightness while a still picture, lettered question, or statement is being shown. Press a button on the remote control and movie projection resumes—6 to 18 frames/sec, forward or backward—until the next marked frame. Single-frame operation is possible so that you could in effect carry 28,800 slides in your pocket. More practical applications are conceivable.

Non-athletic education, training, and motion study endeavors can benefit as well. If you think you see how, ask Eastman Kodak Company, Motion Picture and Education Division, Rochester, N.Y. 14650, where to see a demonstration.

EASTMAN KODAK COMPANY An equal-opportunity employer

SCIENCE AND



Limiting the Real Arms

The U.S. and the U.S.S.R. took a qualitatively new step toward disarmament a month ago by agreeing to discuss limiting their nuclear arsenals. Until now the moves toward arms control have dealt with peripheral issues: nuclear tests, nuclear arms in space, nuclear proliferation. None has come to grips with the central problem: the control and ultimate reduction of their own nuclear weapons systems by the two great nuclear powers. In January, 1964, President Johnson proposed to Premier Khrushchev that the two countries join in developing "limitations on nuclear weapons systems." Three years later, when the Russians were said to be installing an anti-ballistic-missile system around Moscow and the Administration was resisting pressure for a U.S. countermeasure, he repeated the proposal with emphasis on barring construction of ABM systems. Premier Kosygin replied that it was more important to control offensive weapons than defensive ones. There the matter rested until the end of June of this year, when Soviet Foreign Minister Gromyko said in a speech that the U.S.S.R. was "ready for an exchange of opinion" on "mutual restriction and subsequent reduction of strategic vehicles for the delivery of nuclear weapons—offensive and defensive—including antimissile missiles." A few days later President Johnson was able to announce, at the signing ceremony for the nuclear nonproliferation treaty, that such an exchange would be held. The two countries had agreed, he said, to begin talks "in the nearest future" on the "limitation and reduction of both offensive strategic nuclear weapons delivery systems and systems of defense against ballistic missiles."

It was clear that the negotiating process would be long and difficult, but the Washington reaction to the news was generally optimistic. The feeling was that both great powers have much to gain from an agreement to control at least the "overkill" aspects of the arms race, for economic reasons if no other. The issue of inspection, which has always been a major obstacle to agreement on control measures, may now be less critical: both sides have presumably developed such efficient electronic and satellite spy systems as to make them confident of their ability to monitor large new arms installations, particularly the radar facilities required by anti-ballistic-missile systems.

Losing the Lead in Physics

A panel on high-energy physics created by the Atomic Energy Commission has reported that U.S. leadership in this area of physics is passing, at least temporarily, to western Europe and the U.S.S.R. The panel fears that new budget restrictions will damage U.S. research and education in physics so grievously that "there is a clear and present danger that the United States will lose its leadership in this fundamental field. Such a loss would be an ominous step toward the situation in which the United States found itself before the 1930's, when most of the major discoveries in fundamental science were made in Europe. It would have adverse effects on our scientific life, and consequently on our society as a whole."

The panel points out that in the past two years, even before a new round of budget cuts was threatened, the programs at all national laboratories and universities, with one exception, have had to operate at budget levels that were either constant or decreasing. The exception is the program at the Stanford Linear Accelerator Center.

In contrast, the budget of the European Organization for Nuclear Research (CERN) has been increasing at a steady 6 percent a year and construction is proceeding on proton storage rings, "a bold step into a field of untried techniques and unknown physics, for which we have no match yet in the United States." Elsewhere in Europe there are at least eight other accelerators with energies in excess of one billion electron volts (BeV). And the world's largest accelerator is the 76-BeV proton synchrotron recently placed in operation at Serpukhov, near Moscow. The Russian machine will not be surpassed until the American 200-BeV accelerator is completed, perhaps in 1972, at Weston, Ill.

The panel, under the chairmanship of Victor F. Weisskopf of the Massachusetts Institute of Technology, makes several recommendations: (1) that "a substantial increase followed by moderate growth in the annual operating budget for high-energy physics be made as soon as national problems permit," (2) that an electron-positron storage ring be built at Stanford, (3) that a 14-foot bubble chamber be built at the Brookhaven National Laboratory, (4) that the 200-BeV accelerator be authorized in fiscal year 1969 and (5) that funds be allotted to permit U.S. workers to participate in experiments at Serpukhov.

How Does the Helix Double?

In their celebrated letter to *Nature* in 1953, which described the double-helix model of DNA, James D. Watson and Francis Crick wrote: "It has not escaped our notice that the specific pairing [of nitrogenous bases] we have postulated immediately suggests a possible copying mechanism for the genetic material." This June, 15 years and two months later, the 300 participants at the 33rd Cold Spring Harbor Symposium on Quantitative Biology spent a week discussing how DNA is copied in microorganisms and were forced to conclude that no one yet knows precisely how the replication of DNA is achieved. This conclusion is all the more frustrating because the replication of one form of viral DNA has now been carried out in the test tube, using a natural molecule of DNA as a template.

A major topic at the Cold Spring Harbor meeting was the significance of "Okazaki fragments," short fragments of DNA first found in normally growing bacterial cells by R. Okazaki of Nagoya University. These fragments are thought to contain an important clue to the mode

of replication of bacterial DNA. It is well known that replication involves the unwinding of the two molecular strands that form the double helix of DNA and that each parental strand ends up coupled to a new daughter strand. Each parent and its daughter form a new double helix, just as predicted by the Watson-Crick model.

What remains unexplained, among other things, is the direction of synthesis of the daughter strands. The constituents of DNA are the molecular subunits called nucleotides, consisting of a base, a deoxyribose sugar and a phosphate. An enzyme discovered some years ago by Arthur Kornberg of Stanford University links nucleotides in one chemical direction only. No enzyme capable of performing the reverse linkage has been discovered. Now it is also known that the two strands of DNA run in opposite directions, which means that the Kornberg enzyme cannot link the nucleotides in the sequence required to build daughter chains on both strands simultaneously as the two parental strands unwind. In other words, if the unwinding point is visualized as a Y, the enzyme could create a daughter strand running toward the fork on the left arm of the Y, for example, but not on the right arm. On the right arm the direction of synthesis would have to be away from the fork.

According to one hypothesis, this is what actually happens, with the result that the daughter strand on the right arm cannot be formed in a continuous piece. On this hypothesis the strands unwind a short distance before synthesis begins at the bottom of the right arm of the Y and proceeds to the top of the arm. The strands now unwind another short distance before synthesis again begins at the bottom of the right arm. These short segments are then stitched together by a recently discovered enzyme called ligase. It has been suggested that the Okazaki fragments may represent the still unstitched segments of DNA that are synthesized on one strand of the parental DNA. A possible flaw in this view is that some investigators have evidence that Okazaki fragments consist of daughter fragments that originate on both strands of the parental DNA, not merely on one strand.

The Pause That Nourishes

Soft drinks made from soybeans are the basis of at least two commercial efforts to provide more protein in parts of the world where diets are poorly balanced. The Monsanto Company is preparing to sell in Guyana and Taiwan a

drink called Puma, which has been described as tasting like eggnog or vanilla milkshake. In Brazil the Coca-Cola Export Corporation has begun trial marketing of a chocolate-flavored beverage called Saci.

Puma is Monsanto's adaptation of Vitasoy, a high-protein soft drink that was developed in Hong Kong and is popular there. Monsanto has modified the flavor with the aim of making the drink attractive to consumers in a wide variety of cultures. According to the company, a 6½-ounce bottle of Puma contains 3.8 grams of protein and enough of six vitamins to provide a third of the minimum daily requirement for an adult.

Saci, which is named for an elflike character in Brazilian mythology, makes use of two of Brazil's major agricultural products, soybeans and cocoa. The beverage has been described as a sweetened, chocolate-flavored soybean milk. According to the company, a bottle containing a little less than seven fluid ounces provides six grams of protein and enough of seven vitamins to meet a quarter of an adult's minimum daily requirement.

Pliocene Giant

The fossil-rich strata of the Simla Hills in northern India have yielded evidence, in the form of a nearly intact and extremely massive lower jaw, that apes as large as or larger than the modern gorilla lived in middle Pliocene times, more than five million years ago. Jointly announcing the discovery at a July meeting of primatologists at Emory University, S. R. K. Chopra of Panjab University and Elwyn L. Simons of Yale University identified the giant mandible as belonging to a new species of the genus *Gigantopithecus,* hitherto known only from South China fossil finds that are no older than 700,000 years. Thus the Indian jawbone both enlarges the inventory of advanced primates known to have flourished in the era preceding the first emergence of the genus *Homo* and shows that one early genus of great apes successfully inhabited a wide sector of the Orient for many millions of years.

Gigantopithecus, first named by the Dutch paleontologist G. H. R. von Koenigswald on the basis of massive molar teeth he found in a Hong Kong apothecary's shop, was believed by some scholars to be a direct ancestor of *Homo erectus.* Subsequent study of three *Gigantopithecus* mandibles unearthed in southern China makes it evident that, although the giant primate's jaws and teeth have some functional parallels with man's, it is not ancestral to the human genus. By showing that members of the *Gigantopithecus* genus constituted a distinct side branch of primate evolution more than five million years ago, the Indian discovery further secures the position of Africa's australopithecines as mankind's immediate forebears.

Continuous Steel?

The steelmaker's dream of a continuous process from iron ore to steel may be moving closer to realization. According to reports in the steel industry, the United States Steel Corporation is at or near the pilot-plant stage with such a process. Officials of U.S. Steel decline to comment on the reports beyond saying that the company, like other firms in the industry, is working on the objective of continuous-process steelmaking.

A patent assigned to U.S. Steel by the inventors, J. C. Agarwal and W. L. Davis, Jr., may indicate the line of development. The patent points out that "the smelting of iron ore as ordinarily conducted in a blast furnace involves contact between reducing gases and iron oxide in solid form." The idea of reducing, or driving impurities from, ore that is in molten form is an old one, the patent notes, but it has not been realized "because of the destructive effect of the molten ore on refractory materials used to line the vessels containing it" and also because of difficulty in transferring the heat generated in the reduction reaction at a rate high enough to make the process continuous and commercially feasible. The inventors say that with their method of reducing molten iron ore "previous difficulties are overcome and operation on a commercial scale is possible."

The apparatus described in the patent makes use of a melting chamber in which a flame generated by burning a mixture of fuel and high-purity oxygen produces a temperature in excess of 3,500 degrees Fahrenheit. Pea-sized pieces of iron ore and limestone that have been preheated in a fluidized bed are introduced into the flame, which melts the ore. The molten ore falls into a pool below the flame and is then drained into a reduction chamber. There a reductant is introduced below the surface of the molten iron. Oxygen is also introduced into the chamber for partial combustion with unused reductant, thereby maintaining the temperature of the molten ore and supplying the heat needed for the reduction reaction. The problem of damage to the refractory materials is solved by a technique in which the outside of the melting and reducing chambers is cooled with water, which causes a protective layer of iron oxide to freeze on the inside. According to the patent, the metal produced in the apparatus is "iron of better than 99 percent purity from which steel may be made directly by the addition of the desired alloying elements."

Steel experts have suggested that the evolution from a patent or a pilot plant to a large-scale operation is likely to encounter difficulties. One of the difficulties is keeping what the automobile industry calls a float: a supply of items to feed into a continuous-production line if any part of the process breaks down. Moreover, steel is made in about 250 varieties, and it seems unlikely that a continuous-production process could be switched readily from one variety to another.

Crops without Tillage

A new machine method for planting row crops such as corn and soybeans promises to increase U.S. agricultural productivity by cutting the time usually spent in preparing the land with plow and harrow. In northern farm regions with short growing seasons the "no tillage" planting machines ensure maximum growing time and greater yields per acre; in southern farmlands, after the early-summer harvest of winter-grown grains, the machines allow a second crop to be planted quickly amid the harvest stubble, thus guaranteeing two crops a year.

Reporting on the progress of no-tillage farming at the annual meeting of the American Society of Agricultural Engineers in June, W. R. McClure of the University of Kentucky stated that the time-saving technique had become popular in his area soon after modified corn planters became available in 1967, capable of sowing corn and soybeans in harvest stubble and even in unbroken sod. In addition to the time and money saved by omitting conventional tillage, McClure noted, the no-tillage system affords superior erosion control and, because it leaves natural mulch undisturbed, is far less wasteful of soil moisture than plowing and harrowing are. McClure and his associates at the university conclude that Kentucky farmers could eventually increase their earnings by more than $150 million a year by adopting the practice.

Barnacle Cement

The lack of an adhesive strong enough and durable enough to anchor fillings in teeth permanently has led the National Institute of Dental Research to sponsor an investigation of what may well be the stickiest natural adhesive known to man: barnacle cement. The current status of the study, which is being carried out at the University of Akron under the direction of Roger Keller, is reported in a booklet written for the NIDR by Nathan F. Cardarelli, who originally proposed the idea of using barnacle cement as an all-purpose medical and dental adhesive.

One of the most painful aspects of the present method of restoring decayed teeth arises from the fact that it requires the filling to be mechanically locked into the tooth. This mortising involves the removal of sound tooth structure and in some instances a sacrifice of tooth strength. If an adequate adhesive filling material were available, it would be necessary to remove only the decayed part of the tooth in order to place the filling. The cost of repairing teeth would be less and sound tooth structure would be conserved.

According to Cardarelli, "man's efforts at creating adequate medical and dental adhesives are in their infancy." In particular, he states, many extremely strong and durable natural adhesives have never been subjected to even a rudimentary scientific scrutiny. It now appears that one of these, barnacle cement, is superior to all man-made adhesives.

Cardarelli points to an "amazing" fact brought to light by the present study: with one or two exceptions the common acorn barnacle attaches firmly to *all* surfaces that are immersed in ocean water. These include many normally "hard to stick to" surfaces, such as polished glass, mica, metals, small-pore plastics and Teflon, as well as extracted human teeth. The barnacle's cement, a pale brownish liquid, is secreted from a gland through the creature's antennae; on contact with water it hardens to a brownish solid in about 15 minutes. Crude mechanical tests indicate that the cement of one species has an adhesive strength of 22 pounds per square inch of contact area and a tensile strength of at least 50,000 pounds per square inch.

Preliminary chemical analyses of cured cement removed from the basal plates of Florida barnacles show that the material is extremely insoluble in almost all the common solvents. The percentages of carbon, hydrogen and oxygen in the cement, combined with the absence of nitrogen, suggest that it is a polysaccharide and not a protein. The analyses also indicate the presence of a number of trace elements. Further studies of the purified cement are under way, with a view to determining its atomic structure.

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

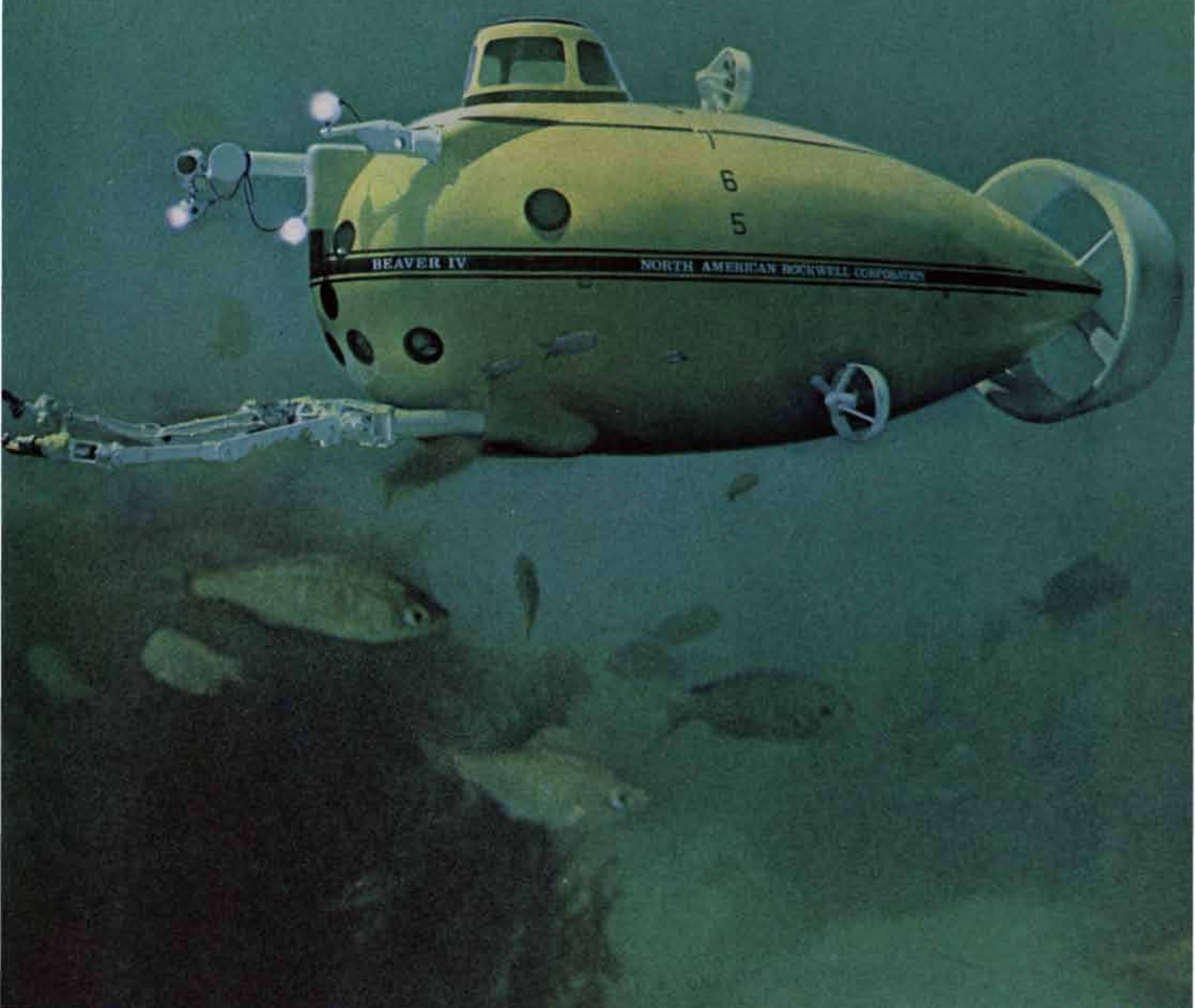
The United States' known oil reserves will hold out for about 15 years. By that time we'll have to make some pretty big advances in discovery and production techniques if we're going to keep burning oil.

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

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

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

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



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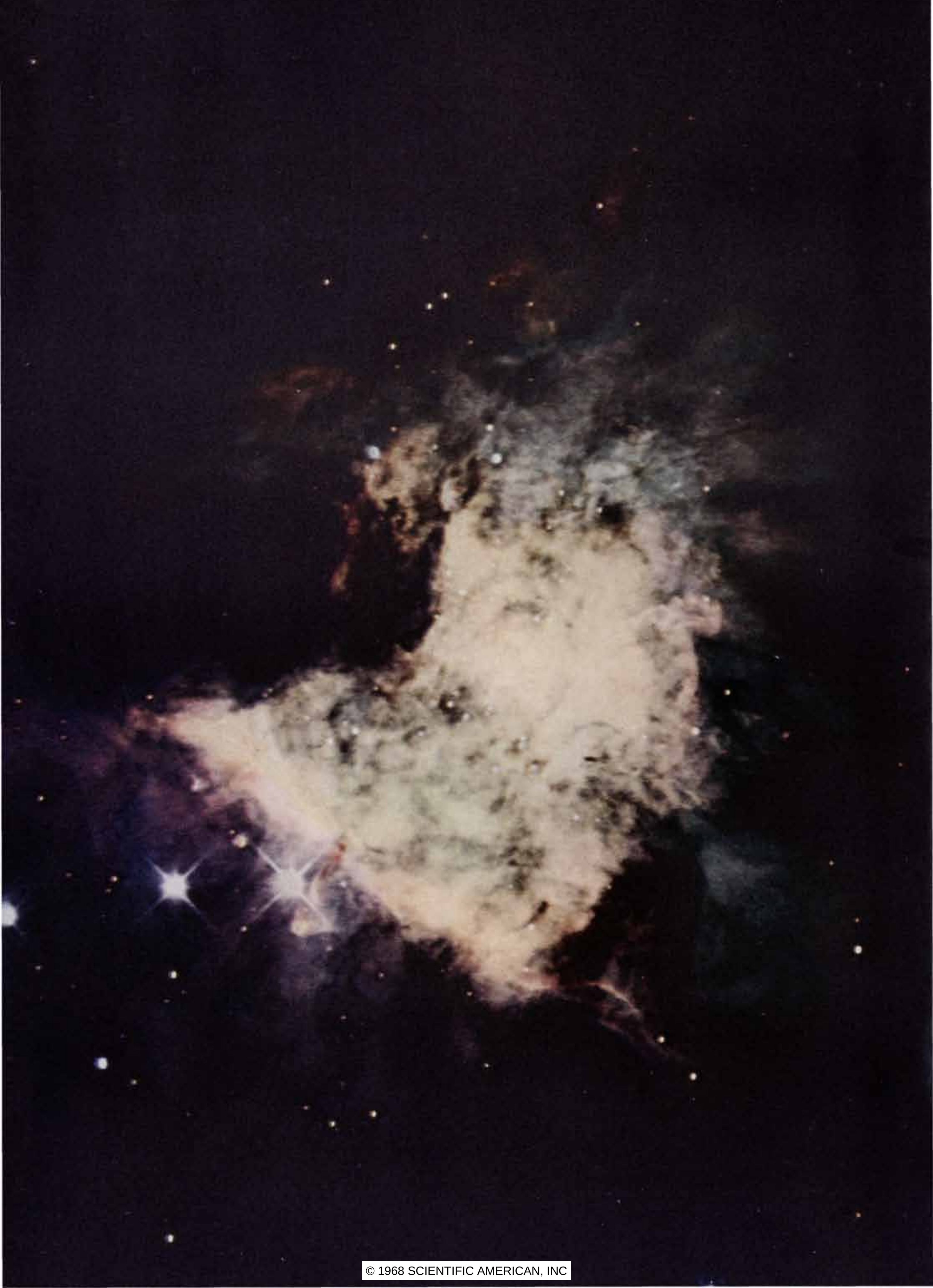


THE INFRARED SKY

A telescope with a 62-inch plastic mirror has provided the first comprehensive survey of the night sky at infrared wavelengths. It has revealed some of the coolest celestial objects yet detected

by G. Neugebauer and Robert B. Leighton

Astronomers have long been aware that if we could see the night sky with eyes sensitive to infrared radiation, it would probably look much different from the sky dominated by the Big Dipper, Orion, Pegasus, Cygnus and other familiar constellations. Until two years ago, however, no one really knew how the night sky would look to an "infrared eye" or what kinds of objects besides stars might appear in it. Although one could be reasonably sure that the few thousand stars visible to the unaided eye would probably not dominate the infrared sky, no one could say how drastically different the infrared sky might look.

To find out we and our associates at the California Institute of Technology have used a specially built 62-inch reflecting telescope on Mount Wilson to conduct a comprehensive survey of infrared sources embracing approximately 75 percent of the celestial sphere. The principal wavelength we used was centered on 2.2 microns, about four times the wavelength of yellow light. The survey disclosed about 20,000 infrared sources in all. As we expected, the great majority are stars. If, in order to proceed with maximum confidence, we count only sources that have 2.5 times the minimum detectable brightness, we are still left with 5,500 sources. For purposes of comparison, a total of about 6,000 stars could be counted in a visual survey made with the unaided eye at the same latitude. In short, our survey has employed an infrared "eye" that detects about as many stars as one can see in the night sky with the unaided eye.

ORION NEBULA contains one of the reddest and thus presumably one of the coolest stars yet discovered in infrared sky surveys. It cannot be seen in photographs made with the largest telescopes. The color photograph on the opposite page was made with the 120-inch reflector at the Lick Observatory. The site of the infrared object lies hidden at the northern end of the glowing mass of gas; the exact location is given by the short white lines at the sides of the photograph, which mark the object's vertical and horizontal coordinates. The visible stars in the neighborhood of the infrared object can be seen more clearly in the black-and-white photograph that is reproduced at the bottom of page 59.

Are they mostly the same stars or mostly different ones? The answer is mostly different. The number of stars visible to both kinds of detector, visual and infrared, is less than 2,000. Thus about 70 percent of the 6,000 stars visible to the unaided eye cannot be detected by our 62-inch infrared eye; similarly, about 70 percent of the 5,500 brightest sources in our survey are not visible to the unaided eye. If man had viewed the night sky with infrared-sensitive eyes, he would have constructed an entirely different assortment of constellations.

Early Infrared Surveys

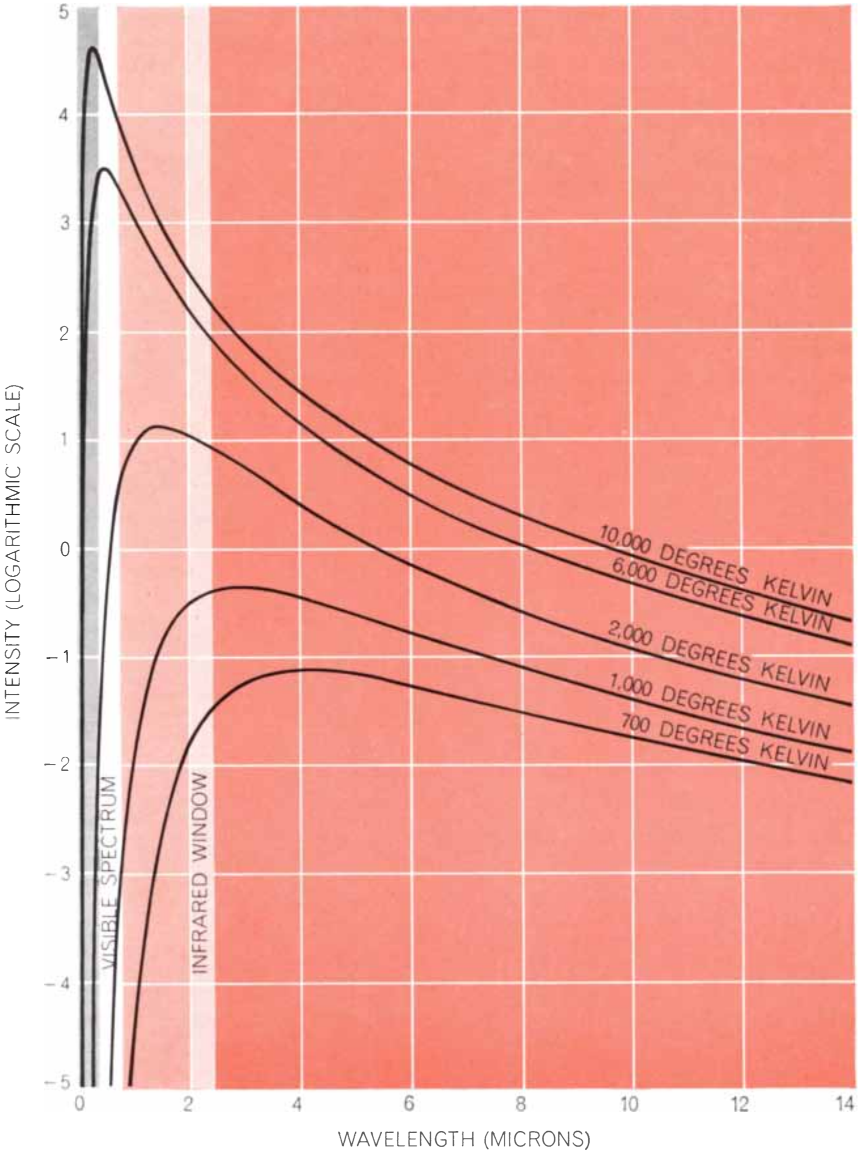
It is largely an accident of uneven technological development that the sky was extensively surveyed at radio wavelengths more than 20 years before this could be done at two-micron wavelengths in the infrared. Prior to our work infrared studies at two-micron wavelengths were carried out mainly on individual objects such as the sun, the planets and a selection of bright stars [see "Infrared Astronomy," by Bruce C. Murray and James A. Westphal; SCIENTIFIC AMERICAN, August, 1965].

As long ago as 1840 Sir William Herschel demonstrated that the sun emits invisible radiation beyond the red end of the visible spectrum. The visible spectrum of course covers only a tiny fraction of the total range of possible wavelengths, which is theoretically infinite. The wavelengths of visible light lie between .4 micron (violet) and .7 micron (red). The peak of the sun's energy falls near the middle of this region, at about .5 micron. Stars cooler than the sun, which has a surface temperature of 5,700 degrees Kelvin, would emit most of their energy in the infrared region beyond .7 micron. Stars as cool as 3,000 degrees K. are well known and a few stars cooler than 2,000 degrees had been found before our survey.

Estimates of the relative numbers of stars of various kinds per unit volume of space have consistently shown that the coolest stars—red dwarfs and the dark companions of hotter stars—account for most of the stellar matter in space. This suggested the possibility that even more matter might be in the form of "dark stars": stars too cool to emit visible light. Astronomers have also believed that protostars (stars in the process of formation) should exist and might be detectable with the appropriate equipment. The temperature of protostars might be as low as a few hundred degrees K. It has been to search for such objects and to extend knowledge of infrared sources in general that astronomers have long sought to push their observations as far into the infrared part of the spectrum as possible.

In the late 1930's Charles W. Hetzler of the Yerkes Observatory searched for cool stars using photographic plates sensitive to the near infrared in conjunction with the 40-inch Yerkes refractor. Perhaps because he never completed the survey, his work did not make much of an impact. He did, however, find a number of stars whose temperatures were between 1,000 and 2,000 degrees K.

Our interest in making an infrared sky survey was more directly stimulated by



WAVELENGTH OF RADIATION emitted by heated bodies varies with the absolute temperature and follows Planck's law of black-body radiation. Ordinary stars range in temperature from about 2,500 degrees to 25,000 degrees Kelvin. Only about 1 percent of the radiation emitted by a 2,500-degree star is in the visible region, whereas about 10 percent lies in the band between two and 2.4 microns, chosen by the authors for their infrared survey.

the work of Freeman F. Hall, Jr., of the International Telephone and Telegraph Corporation, who mounted an array of infrared detectors cooled by dry ice on a 24-inch reflecting telescope. Using this instrument in the San Fernando Valley, Hall scanned some 20 percent of the Northern Hemisphere sky looking for cool objects. He seemed to find a number of sources not shown on star maps, but he also failed to detect some stars that were expected to be very bright in the infrared.

Building an Infrared Telescope

About five years ago we decided it would be worthwhile to make a comprehensive, and thus unbiased, search of the sky for infrared emission using sensitive detectors coupled to the largest possible telescope. It was evident that the existing large astronomical telescopes were unsuited for such a survey, both because of the large amounts of time that would be needed and because of the telescopes' relatively narrow field of view. We therefore decided to build a telescope specially suited to the problem.

It is well known that the free surface of a liquid, rotating uniformly around a vertical axis, assumes the shape of a paraboloid, which is precisely the surface needed to bring parallel rays to a focus by reflection. Exploiting this fact, we poured a slow-setting epoxy resin on a rotating aluminum "dish" that had first been shaped on a lathe to approximately the right configuration. A constant rate of rotation was maintained for three days while the epoxy hardened. After considerable effort and several attempts the technique provided us with a usable 62-inch mirror having a 64-inch focal length. Although the mirror is somewhat lacking in perfection, its aluminized epoxy surface is satisfactory for the long wavelengths and coarse detectors used in infrared astronomy. With the help of students we built a telescope mounting and a small building to house it on Mount Wilson [*see bottom illustration on opposite page*].

Of equal importance to the design of an efficient telescope is the choice of the spectral region to be studied and the design of the detector system to be used. Astronomers who want to observe the infrared emission from celestial objects face several handicaps. One is the lack of sensitive infrared-detection systems. This limitation has been alleviated in the past 10 years, but infrared detectors are still less sensitive than good visible-light detectors by a factor of at least 1,000. If infrared detectors were as sensitive as visible-light ones, we could have made our survey with a two-inch mirror.

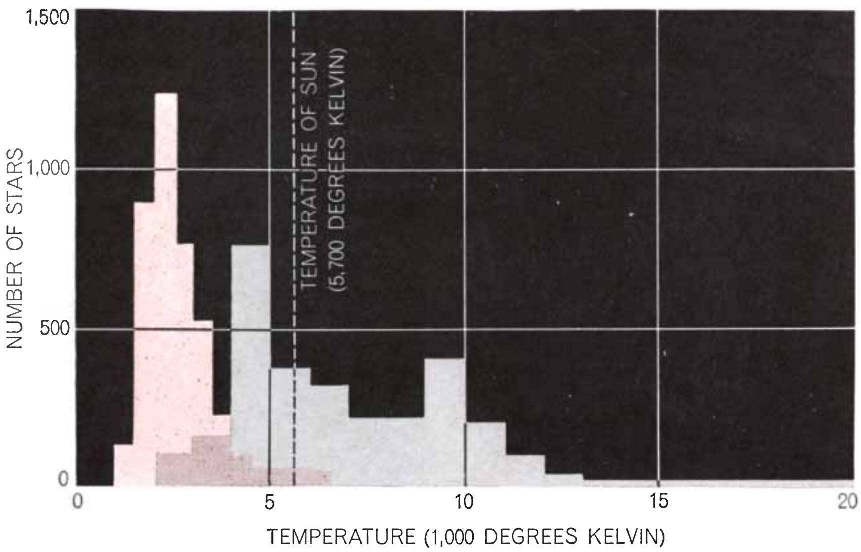
A more fundamental limitation is that gases in the earth's atmosphere, chiefly water vapor, absorb most of the incoming infrared radiation. Beyond the .7-micron limit of the visible spectrum the atmosphere remains fairly transparent out to about 1.3 microns, beyond which it is opaque except for a few transmission "windows." The first few of these are centered at the following wavelengths in microns: 1.65, 2.2, 3.6 and 4.8. There is a relatively broad window between eight and 14 microns and another between 17 and 22 microns. From 22 microns to 1,000 microns (one millimeter) the atmosphere is largely opaque. The last good window available to the infrared astronomer, the region from one millimeter to three millimeters, carries him into the domain of the radio astronomer, who employs antennas and wave detectors rather than the photodetectors that are normally used in conjunction with optical reflecting telescopes.

A final problem confronting the infrared astronomer is that the entire world radiates. Opaque nonmetallic bodies radiate energy whose wavelength is distributed according to Planck's law of black-body radiation [*see illustration on this page*]. The spectral distribution of black-body radiation depends on the absolute temperature (T) of the body in such a way that the maximum energy (per unit wavelength interval) is radiated at a wavelength (λ_{max}) given by Wien's displacement law ($\lambda_{max}T \cong 3{,}000$, where λ_{max} is in microns and T is in degrees Kelvin). Thus the peak of the sun's energy, corresponding to its temperature of 5,700 degrees K., is at about .5 micron, whereas objects at room temperature (300 degrees) radiate with a maximum intensity near 10 microns and emit negligible radiation at visible wavelengths. Therefore the infrared astronomer faces a problem comparable to that of an optical astronomer working in a lighted dome with a luminescent telescope.

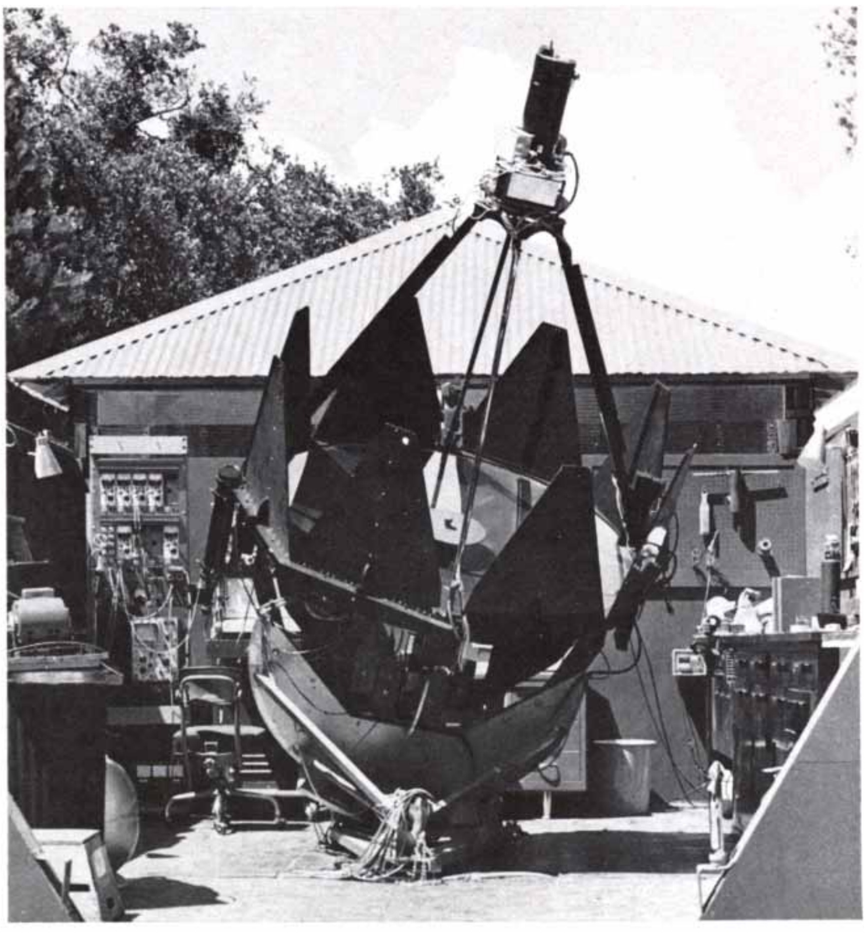
We selected the window between two and 2.4 microns for our sky survey. Factors that influenced this choice were the favorable response characteristics of lead-sulfide photoconductive detectors, the good transparency of the atmospheric window at this wavelength and the fact that it provides a significant step beyond the visible. Stars with temperatures around 1,000 to 1,500 degrees K. would emit the peak of their energy in this wavelength region. In order to cover a suitably wide swath in the sky, a linear array of lead-sulfide detectors was used. In addition a silicon photodetector was employed to measure the incoming radiation between .7 and .9 micron, providing a basis for defining a "color" of the detected objects. All the detection is done electronically; no visual observations are made with the telescope.

To eliminate sky emission and the background radiation of objects at room temperature the mirror is rocked gently at 20 cycles per second while the telescope and detectors remain fixed. The background radiation, being constant over a large part of the focal plane, gives rise to a steady, or direct, current in the detector. On the other hand, a small focused source, being shifted alternately on and off the detector by the vibration of the mirror, gives rise to an alternating current. The subsequent amplification of the signal current is arranged to ignore the direct-current component and to enhance the alternating one. This scheme works so well that at two microns it is possible to detect stars almost as effectively during the day as at night. (The Rayleigh scattering of sunlight, which is responsible for the blue color of the sky, is almost 100 times weaker at two microns than at .5 micron.) At .7 to .9 micron, however, there is too much background radiation during the day to allow daytime operation.

The entire telescope is automatically



APPARENT TEMPERATURE RANGE of the 5,500 brightest stars in the authors' infrared survey is represented in color. Judged solely by their redness, most fall between 1,500 degrees and 3,500 degrees K. The temperature range of some 6,000 stars visible to the unaided eye is shown by the gray area. The areas overlap slightly between 2,000 and 6,500 degrees K.



INFRARED SURVEY TELESCOPE on Mount Wilson has a 62-inch plastic-on-aluminum mirror with a 64-inch focal length. The mirror's parabolic surface was formed by pouring liquid epoxy resin on an approximately contoured aluminum disk and rotating the disk at constant speed for three days while the epoxy hardened. The epoxy surface was then aluminized. The infrared sensors, chilled by liquid nitrogen, are supported on four legs at the focus of the mirror. When the telescope is not in use, the eight petal-shaped flaps are lowered to protect the mirror. The corrugated roof can be slid forward to provide a weatherproof housing for the instrument. The telescope and the housing were designed and built by the authors with the help of students at the California Institute of Technology.

programmed to scan the sky in a raster pattern. The telescope sweeps east to west through 15 degrees of arc at about 20 times the rotation rate of the sky and then steps north by 15 minutes of arc; it sweeps 15 degrees in the opposite direction, again steps 15 minutes north, and so on. In this way, during each hour of observing, a strip of sky measuring three degrees from north to south and 15 degrees from east to west is covered. During the course of a year the instrument can survey essentially all but the 25 percent of the sky that is too close to, or below, the southern horizon. It has now been used to scan the entire northern sky twice.

Analysis of the Infrared Survey

As we have noted, some 20,000 infrared sources have been detected with our 62-inch infrared telescope. Only the 5,500 brightest sources will be compiled into a catalogue of infrared stars. Those that are less than 2.5 times the minimum detectable brightness will be omitted, because it is important, particularly for statistical work, to have confidence in the completeness of such a survey. Relatively few of the 5,500 (fewer than 30 percent) emit enough visible light to be seen with the unaided eye on a clear night. And approximately a third have visual magnitudes fainter than 10.5, which means they are about 100 times too faint to be seen with the unaided eye.

Whether or not a given star detected in our survey is among the 6,000 that can be perceived visually depends on its temperature—at least its apparent temperature. Typical stars range in temperature from about 2,500 to 25,000 degrees K. For a star with a temperature of 25,000 degrees roughly 2 percent of the total energy output is in the visible region, and less than .05 percent is in the infrared band observed in our survey. In contrast, only 1 percent of the radiation emitted by a 2,500-degree star is in the visible region, whereas 10 percent is in the two-micron infrared band. As a result a star that is on the threshold of detection in our survey would be easily visible as a second- or third-magnitude star if its temperature were about that of the sun, but if its temperature were 1,000 degrees, it would be invisible to a visual observer even with the 200-inch telescope!

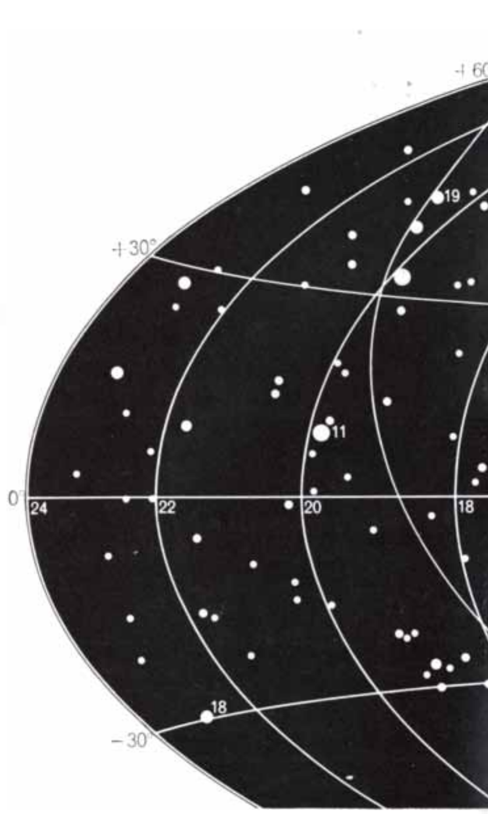
These ideas become more concrete if we plot the apparent temperatures of the stars in our infrared survey and the apparent temperatures of the unaided-eye stars [*see top illustration on preceding page*]. It then becomes clear that stars that are bright in the infrared are cooler than stars that are bright visually. These temperatures cannot always be interpreted, however, as kinetic, or actual, temperatures.

A very red and apparently cool star need not be cool. It is well known that interstellar dust will scatter blue light and make a star appear redder, and thus cooler, than it actually is. This effect, however, provided another reason why a search of the sky in the infrared might turn out to be extremely revealing: the extinction of starlight in the infrared is much less than in the visible. In fact, in the direction of the center of our galaxy radiation of two-micron wavelength is attenuated by a factor of only 10, whereas we estimate that visible radiation is attenuated by a factor as large as 10 billion. Not only can stars be reddened by interstellar dust but also their spectral distribution may depart from Planck's law of black-body radiation. The general trends of temperature are nonetheless correct.

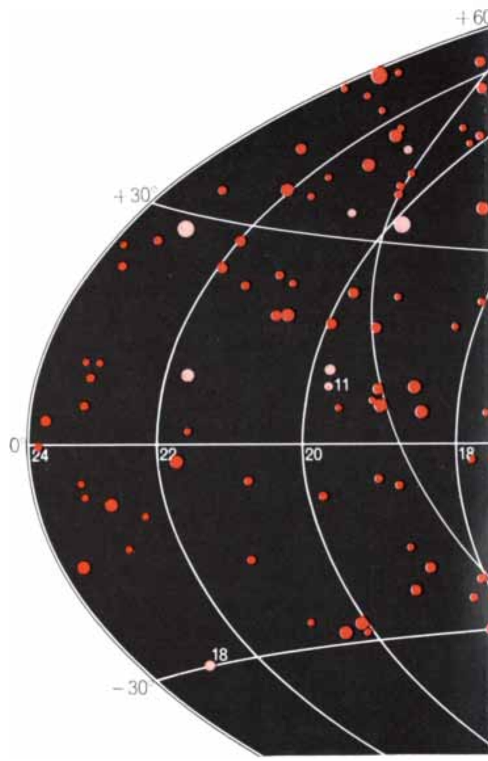
The illustrations on these two pages show the distribution in the sky of the brightest stars observed visually and the brightest stars observed at a wavelength of 2.2 microns; about 300 stars in each category are represented. Although the familiar constellations are no longer evident in the infrared, both distributions look more or less random and qualitatively the same. A few of the well-known bright reddish stars, such as Betelgeuse, are present on both charts, but as one would expect the hotter white stars do not stand out conspicuously in the infrared.

The distribution of the 300 faintest stars seen with the unaided eye and of the 300 faintest stars observed in the infrared survey are plotted together in the top illustration on pages 56 and 57.

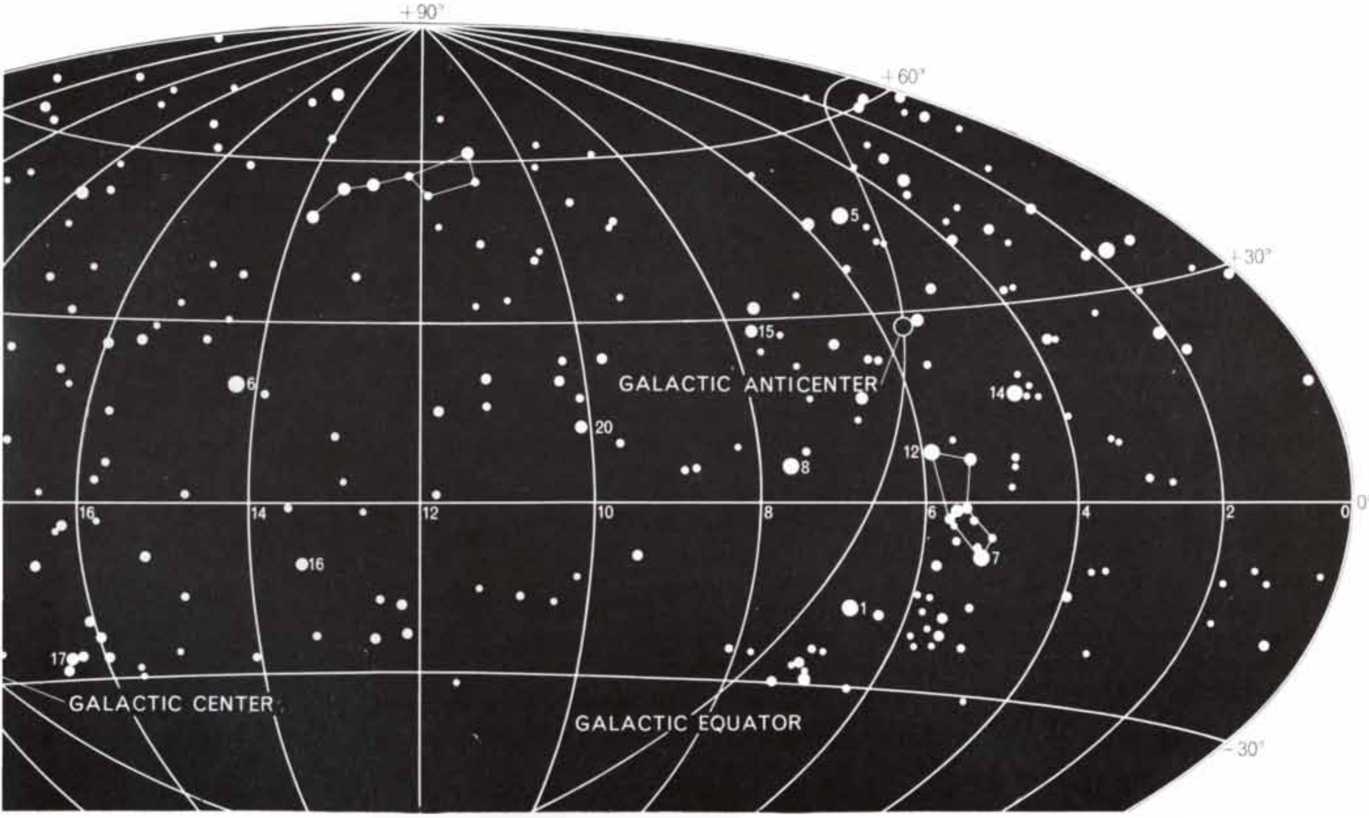
1. SIRIUS
2. CANOPUS*
3. ALPHA CENTAURI*
4. VEGA
5. CAPELLA
6. ARCTURUS
7. RIGEL
8. PROCYON
9. ACHERNAR*
10. BETA CENTAURI*
11. ALTAIR
12. BETELGEUSE
13. ALPHA CRUCIS*
14. ALDEBARAN
15. POLLUX
16. SPICA
17. ANTARES
18. FOMALHAUT
19. DENEB
20. REGULUS



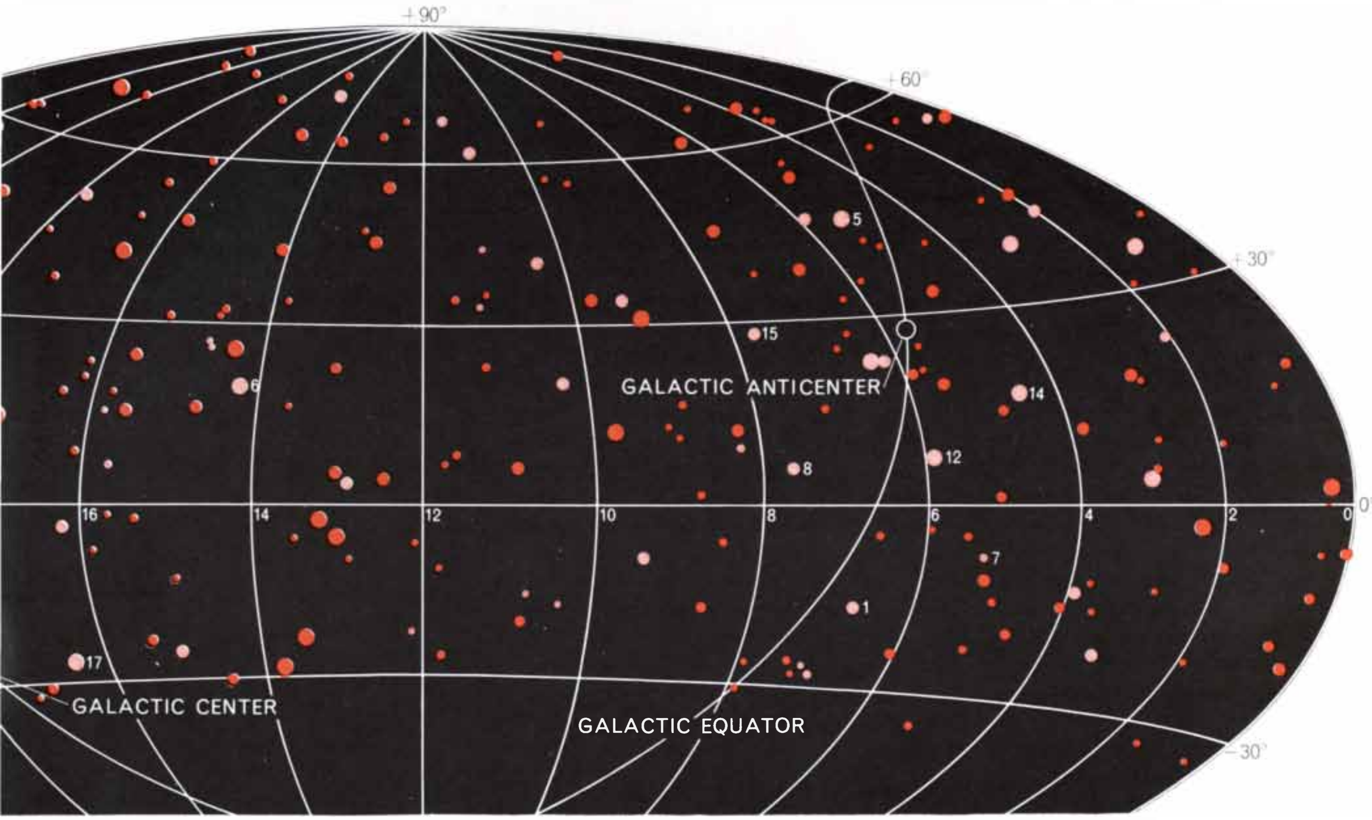
BRIGHTEST VISIBLE STARS, meaning stars visible to the unaided eye, are distributed more or less at random. The numbers



BRIGHTEST INFRARED STARS, meaning stars that are brightest at the survey wavelength of two to 2.4 microns, are also dis-



identify 15 of the 20 brightest stars of all; their names are given at the top of the adjacent column. Five, marked by asterisks, are not shown in the sky chart because they are permanently below the southern horizon at the latitude of Mount Wilson. In this and subsequent sky charts the number of stars plotted is about 300. Numerals on the horizontal axis represent right ascension in hours.



tributed more or less randomly, but only about 20 percent of them (*pale color*) are among the 300 brightest visible stars. Some of the others, however, would be visible as faint stars to the unaided eye. A star may appear red because it is genuinely cool or because its light has passed through interstellar dust, which preferentially scatters and reduces the blue component of the original light.

Only three stars are common to the two categories. Although the distributions are again roughly similar, the randomness is gone and the Milky Way—the central plane of our galaxy—begins to stand out. Perhaps it is even a little more pronounced in the infrared than it is in the visual. The Milky Way becomes very conspicuous if we plot the distribution of stars selected on the basis of redness, as is done in the bottom illustration on these two pages. In this illustration it is apparent that the survey can be used as a powerful tool for probing the structure of the galaxy.

The increasing importance of the Milky Way in the plots of the fainter stars can be explained on a simple basis. On the average the bright stars are relatively close to us and we see roughly the same number in any direction, since within this range of observation the galaxy is nearly uniform. The fainter stars, however, are generally so far away that we can see them well beyond the confines of the galactic disk when we look at right angles to its central plane. In this direction we run out of stars to be seen. On the other hand, when we look along the galactic plane, the density of stars remains high as far as the telescope can see; in fact, the gradual increase in the density of stars in the direction of the galactic center, and the decrease in the direction of the anticenter, stand out clearly.

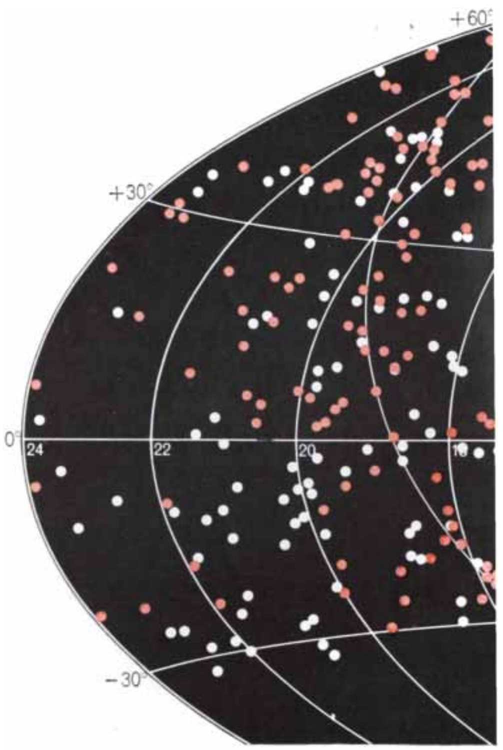
By means of indirect arguments the facts given above can be used to delineate certain features of the galaxy as it is viewed in the infrared. For example, the cool stars observed in the survey enable us to estimate that the thickness of the galactic disk is approximately 400 parsecs (one parsec is 3.26 light-years), which is about the same as has been estimated on the basis of hotter stars. Another finding is that in the plane of the galaxy our telescope can detect very red giant stars out to an unexpectedly great distance: some 2,000 parsecs. Over the range observed we find that the galaxy thins out with distance from the galactic center: near the sun, which is about 10,000 parsecs from the center, the star density decreases by a factor of 2.5 with each 1,000 parsecs. To be sure, these simple concepts are confused by interstellar reddening, and we have had to make some guess as to how this reddening affects the data. Whereas the effects of the reddening and the question of the intrinsic redness of objects cannot be separated out uniquely, the infrared data should be much less confused by reddening than similar visual data are.

Infrared star counts may also have a bearing on the structure of the galaxy. It is known that at our distance from the galactic center the galaxy makes a complete turn in about 200 million years. On this basis, and from the size and shape of the galaxy, one can compute how much mass the galaxy must have. It turns out that less than half of the mass required by this analysis can be accounted for by detectable stars, gas and dust. One suggestion that has been made is that invisible stars—perhaps infrared stars—may be quite numerous and might account for a significant part of the total mass. The absence of large numbers of faint but randomly distributed stars in our survey indicates that such objects are either absent or lie below the detection threshold of our equipment. The faintest infrared stars we do see, being intrinsically bright stars but at a great distance, account for a very small part of the total mass. Thus the missing mass remains unaccounted for.

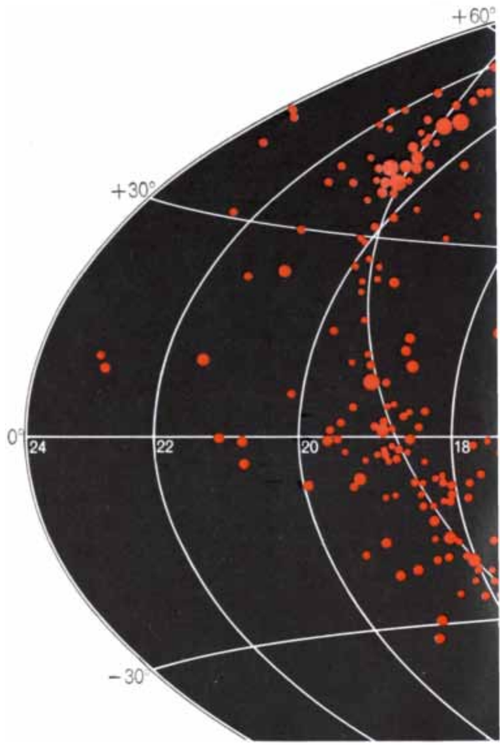
The Coolest Objects Observed

Although the statistical results that have come from the survey have been valuable, we have been most interested in the individual very red objects detected. At first we expected that most of these objects would belong to the family of cool variable stars with periods ranging from a few months to several years. (One reason the sky was surveyed in two different years was to estimate how many stars might have been missed on a single survey because they were at a low point of their light curve; another was to obtain a statistical measure of the fraction of survey stars that are variable.) We thought if we were lucky we might also be able to detect protostars. These objects might be in the form of extended blobs of dust and gas at a temperature of only a few hundred degrees K., and might represent a turbulent mass of matter assembled by its own gravitational attraction just before the formation of one or more stars. The survey was designed to detect concentrated objects as cool as 400 degrees K., which meant that we could hope to detect stellar objects that were only a little above the boiling point of water (373 degrees), if any such objects existed in the sky and were near enough to us.

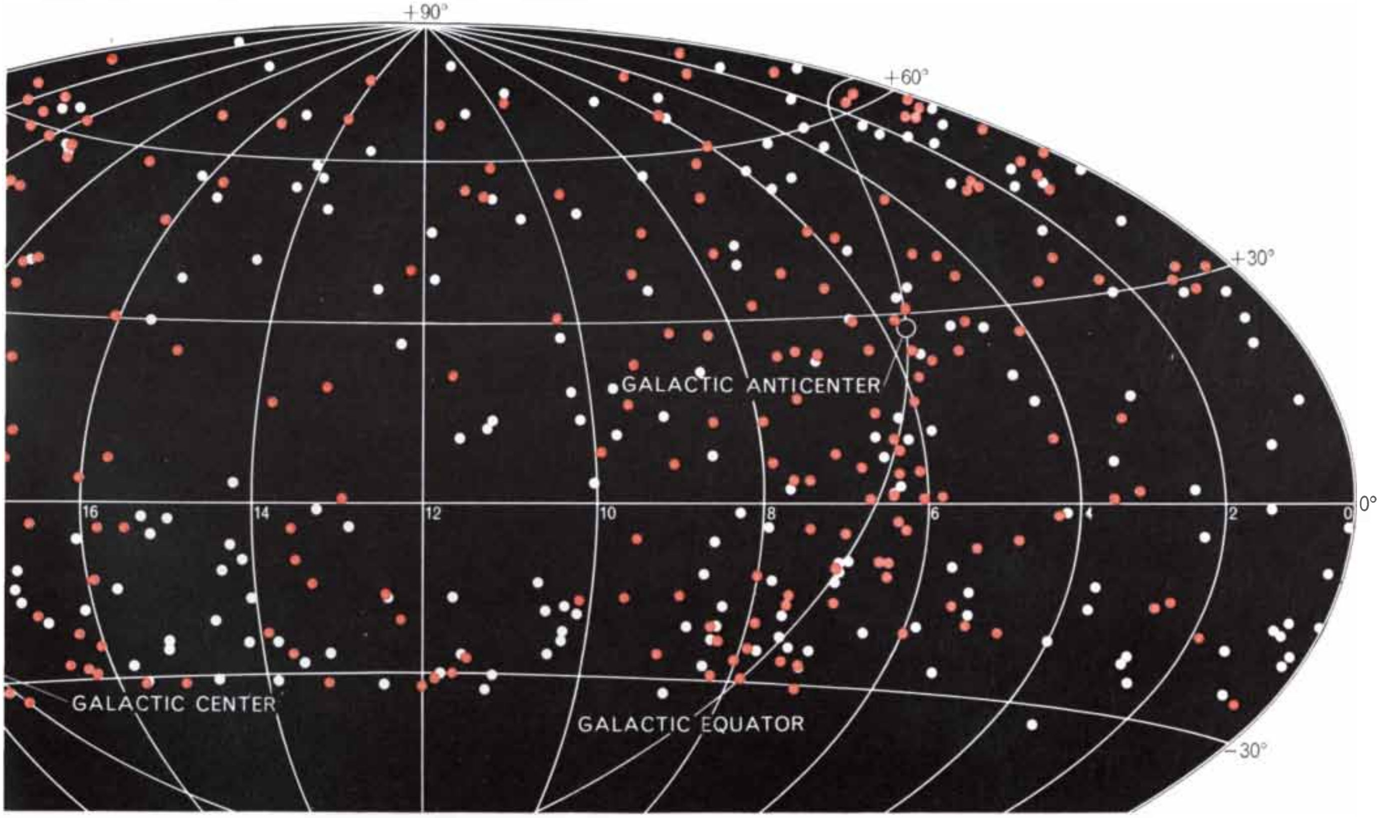
Of the 5,500 stars observed, 450 are so red that at least 97 percent of their total energy output is in the infrared beyond one micron, which corresponds to black-body temperatures below about 1,700 degrees. Almost all these stars are, as we had expected, long-period vari-



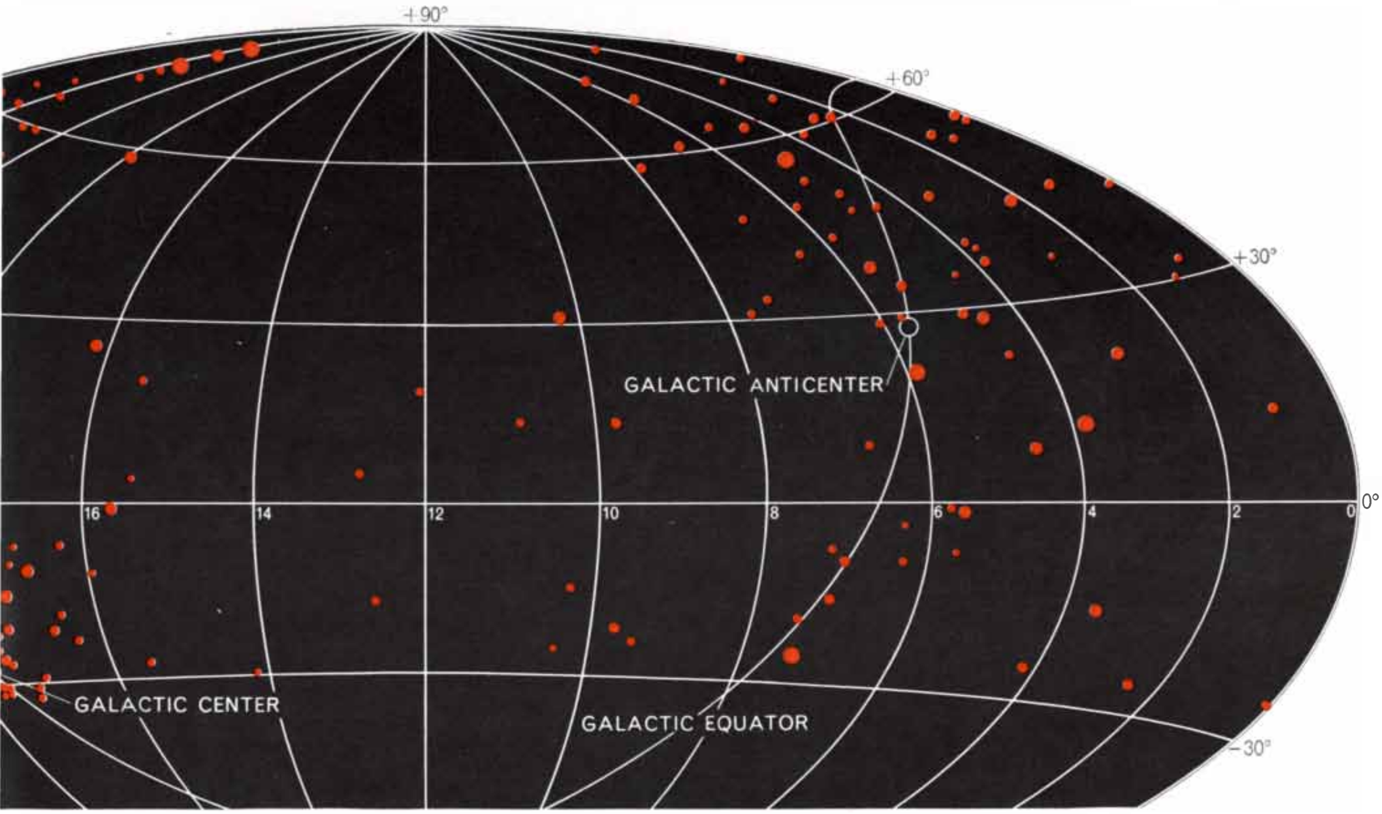
FAINTEST STARS, both visible (*white*) and infrared (*color*), tend to be more numerous near the galactic equator for the



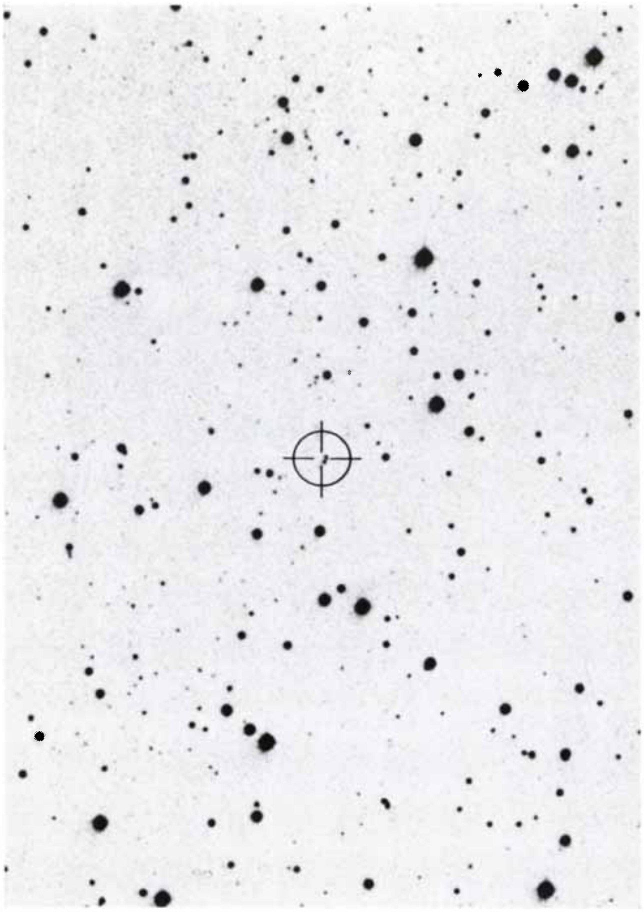
REDDEST INFRARED STARS in the survey show an unmistakable concentration along the galactic equator and particularly

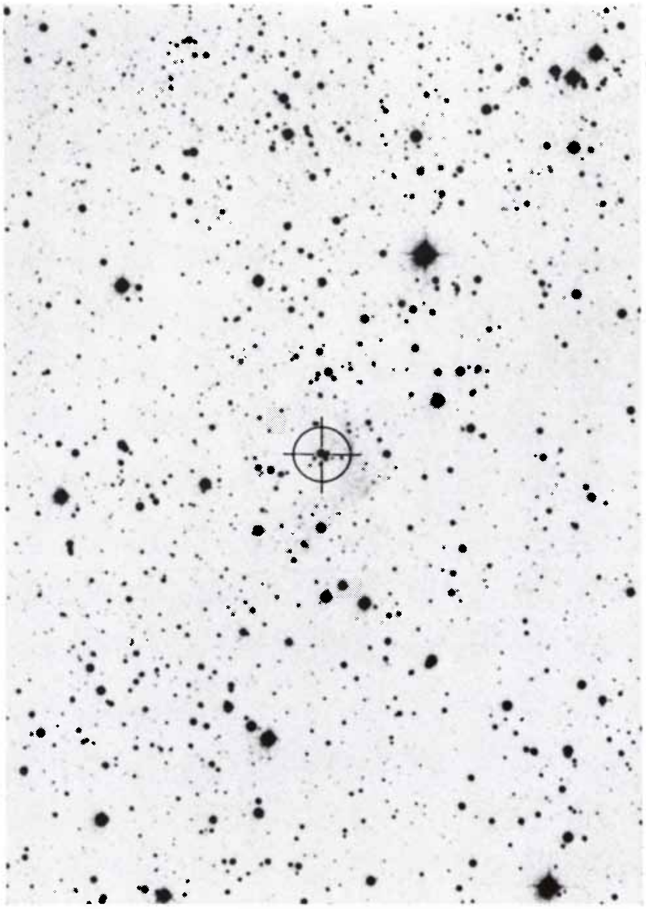


simple reason that there are more stars to be seen when looking into the galactic plane than when looking at right angles to it. Only three of the 300 faintest infrared stars in the survey are included among the 300 faintest visible stars. Among the 5,500 brightest infrared stars in the survey, about 30 percent are among the 6,000-odd stars visible to the unaided eye from the same latitude.

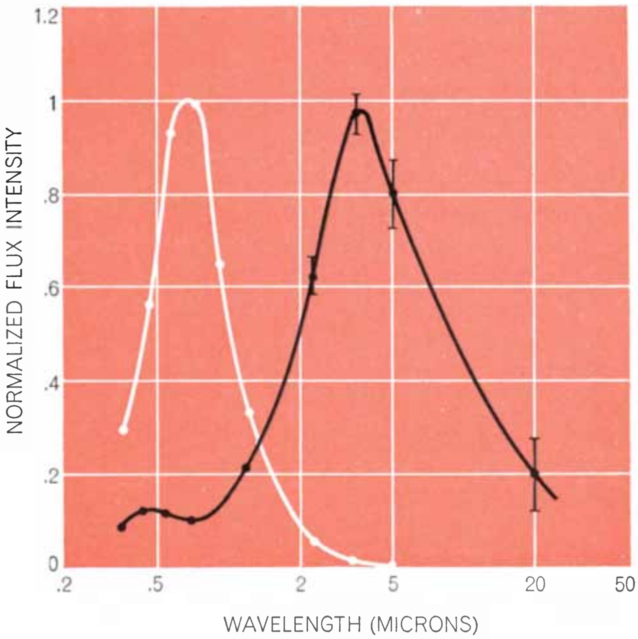


in the general direction of the galactic center. It is estimated that interstellar dust dims visible starlight originating near the center of the galaxy by a factor as large as 10 billion. Infrared radiation of two-micron wavelength, however, is attenuated by a factor of only about 10. The apparent temperature of all the stars plotted here is below 1,700 degrees K. Many are found to be long-period variables.





INFRARED SOURCE IN CYGNUS emits as much radiation at two microns as does Vega, the fourth-brightest star. The object is invisible on blue-sensitive plates (*left*) taken with the 48-inch Schmidt telescope on Palomar Mountain. It stands out clearly, however, on red-sensitive plates (*right*). At a wavelength of 20 microns the Cygnus source outshines every known stellar object except the sun.



POSSIBLE PREPLANETARY SYSTEM coincides with an object at the head of Hubble's variable nebula (*left*). In this photograph from the Lick Observatory, the infrared object, known as R Monocerotis, looks like the head of a diving bird. The object had been classified as a T Tauri star until Eugenio E. Mendoza of the Tonanzintla y Tacúbaya Observatory in Mexico found that the spectrum of R Monocerotis (*black curve at right*) has a large maximum near four microns. White curve shows the spectrum of the sun.

ables. Over three years of observation the brightness of some stars at 2.2 microns has been observed to change by a factor of nearly 10. This in itself is a significant finding because the coolest variable stars previously measured (the Mira variables) change brightness very little in the infrared.

Some of the very red stars are not long-period variables, however. In fact, one of the reddest (and coolest) stars so far detected does not vary. This star, located in the vicinity of Cygnus [*see top illustration on opposite page*], is as bright at two microns in the infrared as Vega, the fourth-brightest star in the sky. Frank J. Low of the University of Arizona has found that at 20 microns the Cygnus source is brighter than any other known stellar object except the sun. Its energy distribution seems to be similar to the one expected from a star whose temperature is about 1,000 degrees. Fred F. Forbes of the University of Arizona has found that its radiation in the near infrared is about 5 percent polarized.

What is this cool object? We do not yet know, except that it seems to be unique in the combination of its great brightness, extreme redness and lack of variability. Harold L. Johnson and V. C. Reddish of the University of Arizona have argued that it may be an extremely bright supergiant star that has been reddened by either interstellar dust or a circumstellar envelope of some kind. If this is the case, the supergiant would be of a kind never before observed. Other workers, notably M. V. Penston of the Royal Greenwich Observatory, have suggested that stars in the process of formation should be surrounded by a shell of cool dust. Hence the Cygnus source may be an example of a protostar, although it is not accompanied by other young stars as one would expect.

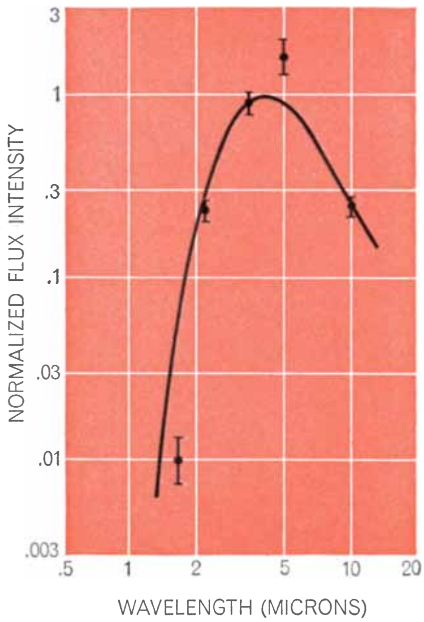
Almost all the other bright, very red objects that have been studied more closely after their detection in the survey have been shown either to vary in brightness or to be stars highly reddened by interstellar dust. Thus one important but essentially negative result of the survey has been to establish that extremely red objects that might be associated with star formation, and that are also very bright at two microns, are not common.

A Preplanetary System?

It was our desire to avoid the bias involved in preselecting certain areas of the sky or categories of objects judged to be "interesting" that led us to survey the entire sky. Our goal was to find out what was there. More conventional telescopes equipped with infrared detectors can be much more sensitive than our simple survey telescope. With such instruments several exciting new discoveries have been made on close examination of particular objects.

One of these objects is R Monocerotis, which lies at the head of the comet-shaped nebula called Hubble's variable nebula [*see bottom illustration on opposite page*]. For many years R Monocerotis had been classified as a T Tauri star on the basis of its optical spectrum [see "The Youngest Stars," by George H. Herbig; SCIENTIFIC AMERICAN, August, 1967]. In 1966 Eugenio E. Mendoza of the Tonanzintla y Tacubaya Observatory in Mexico found that the spectrum of R Monocerotis has a second maximum in the infrared that actually accounts for most of the total energy radiated by the object. The peak of this infrared component is around four microns; the entire energy distribution corresponds roughly to that of a black-body source at 750 degrees K. except for a curious excess at 22 microns. Low, who has made most of the astronomical observations at 10 microns and beyond, and Bruce J. Smith have suggested that this energy distribution may be produced by a dust cloud surrounding the star that absorbs the short-wavelength radiation and reemits the energy at the longer infrared wavelengths. Low and Smith further suggest that this object may be an example of a preplanetary system. It may be significant that T Tauri stars are known to be among the very youngest stars in the galaxy.

A quite similar object has been found in the Great Nebula in Orion, which has



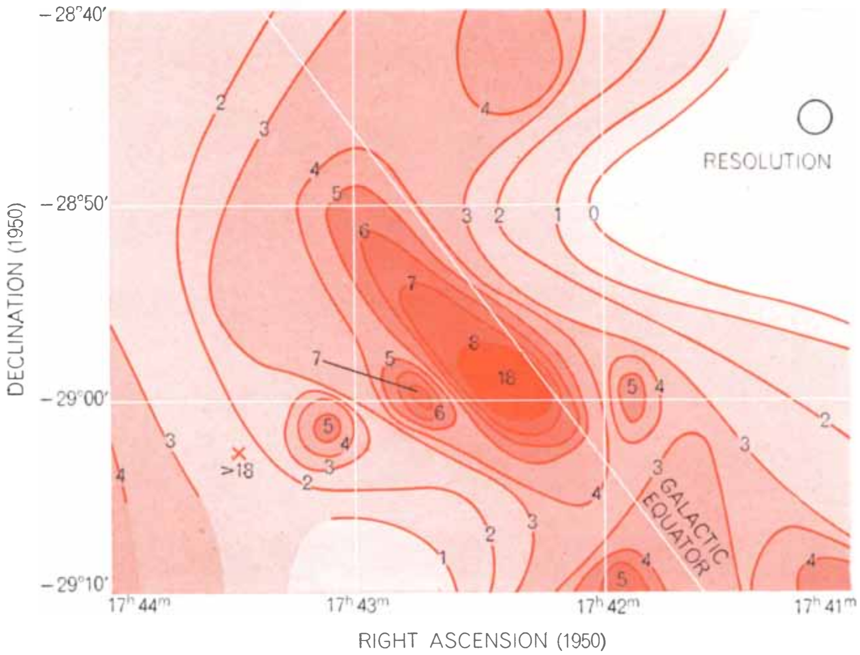
INFRARED STAR IN ORION was discovered by Eric E. Becklin of the California Institute of Technology, using the standard 60-inch telescope on Mount Wilson. The location of the object is shown by the small colored circle in the Lick photograph at the left. Within it no star can be seen even with the 200-inch telescope. The infrared source seems to be a point embedded in a larger region that also emits in the infrared. The radiation curve of the point source (*right*) conforms to that of a black body at 650 degrees K.

been suspected as being a breeding ground for new stars [*see illustrations on page 50 and preceding page*]. The object was found by one of our colleagues, Eric E. Becklin, using the Mount Wilson 60-inch telescope. At photographic wavelengths this object is quite invisible even with the 200-inch telescope, but in the infrared it is almost bright enough to appear on our sky survey. Although the source seems to be a point, it is surrounded by an extended distribution of infrared radiation that is centered on it.

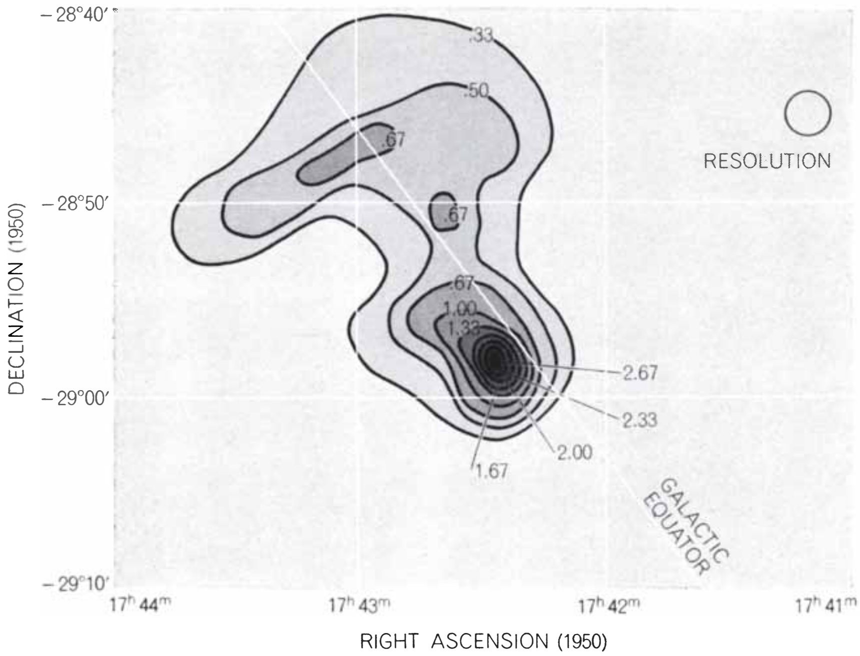
The emission of the point source has been measured at various infrared wavelengths out to 13.5 microns. These measurements yield a radiation curve that conforms closely to that of a black-body whose surface temperature is around 650 degrees K. Again we must consider whether the object really has this temperature or whether it is a normal star whose visible component of radiation has been absorbed and scattered by dust. One can calculate that if it were a red supergiant it would have to be hidden behind enough dust to dim it by a factor of 100 trillion to create the observed appearance. This explanation seems to us most unlikely. We believe the object is a star with an extremely cool surface—quite possibly a protostar. If reasonable guesses are made as to its size and mass, one finds that observable changes should occur in much less than 1,000 years, a short time by astronomical standards.

Last year Low and Douglas E. Kleinmann attempted to study the Orion infrared star at 20 microns. They were unable to detect a measurable signal from the point source but found, adjoining the point source but apparently distinct from it, an extremely bright extended source. Indeed, at 22 microns this infrared "nebula" turns out to be the brightest known object in the sky with the exception of the sun and the moon. We can only guess at its temperature, but from the relative absence of energy at other wavelengths one can estimate that it is less than 150 degrees K., or about 120 degrees below zero Celsius. Again the current belief is that the nebula is an example of a dense cloud in which stars are forming.

A further exciting fact was added recently when Ernst Raimond and Baldur Eliasson of Cal Tech, working with the radio telescope at Owens Valley, Calif., discovered that the Orion infrared point source is also emitting line radiation characteristic of the hydroxyl radical (OH). With this clue, known OH-emission sources are now being examined in the infrared to see if other such instances can be found.



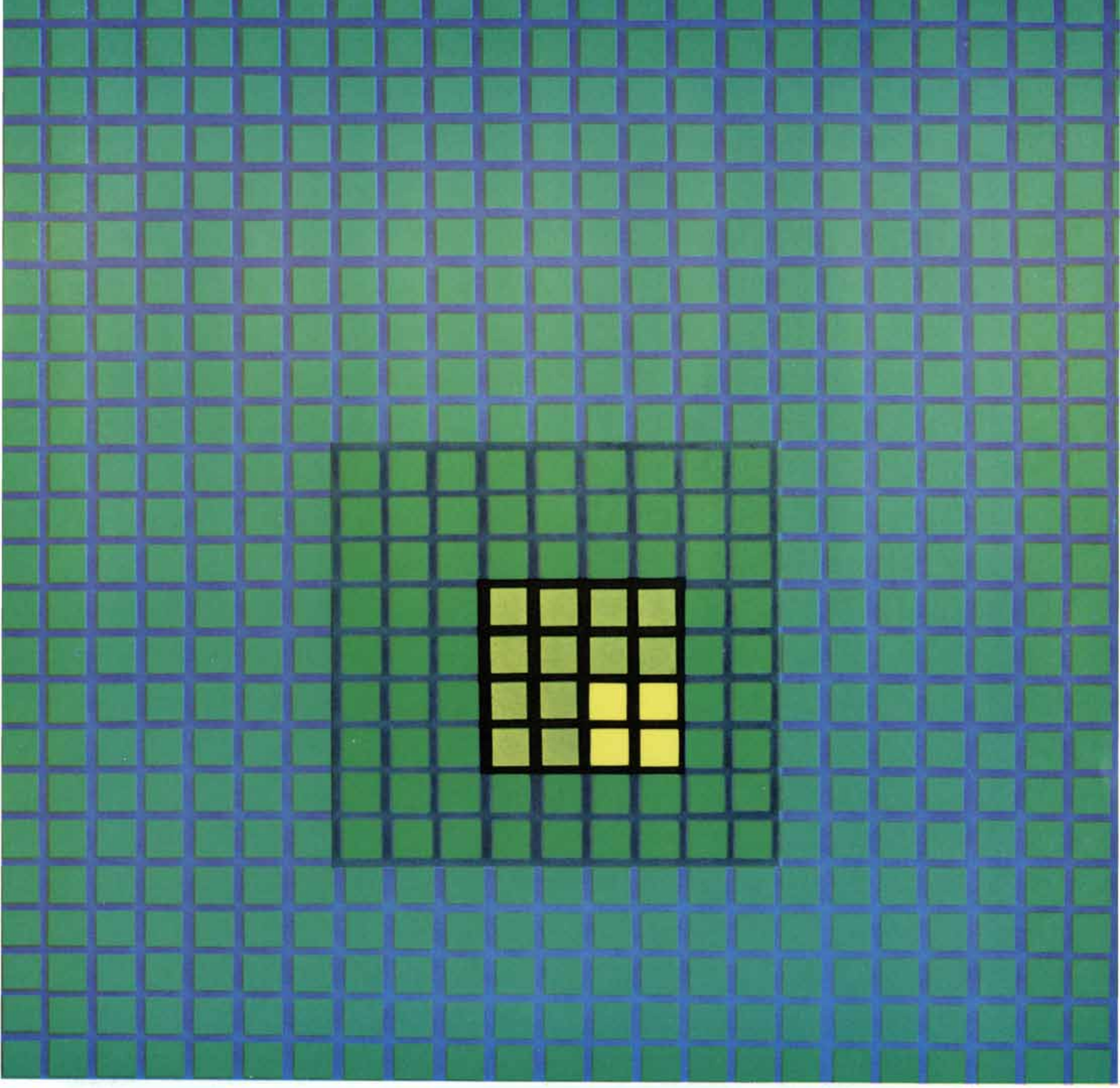
INFRARED MAP OF GALACTIC CENTER shows intense emission at 2.2 microns slightly to the left of the galactic equator. Slightly farther to the left is an intense point source, marked by a colored cross. The zero line represents the sky background radiation. The other lines are labeled in units of 5.2×10^{-10} watt per square centimeter per micron per steradian.



RADIO MAP OF GALACTIC CENTER is plotted to the same scale as the infrared map at the top of the page. Both survey methods locate the galactic center in very nearly the same place. The numbers on the contour lines represent the antenna temperature in degrees Kelvin. A slight correction was made for extinction by dust. The survey was made at a wavelength of 1.9 centimeters by D. Downes, A. Maxwell and M. L. Meeks, using the 120-foot antenna at the Lincoln Laboratory, operated by the Massachusetts Institute of Technology.

The Galactic Center in Infrared

Many other galaxies exhibit a definite nucleus when they are observed at visible wavelengths. In the case of our own galaxy the interstellar extinction is so great that one cannot see into the galactic center, although several studies have shown the presence of a central "bulge." Several years ago, however, radio astronomers found a radio source, Sagittarius A, whose location coincides quite closely with the point identified as the galactic center on the basis of stellar-mo-



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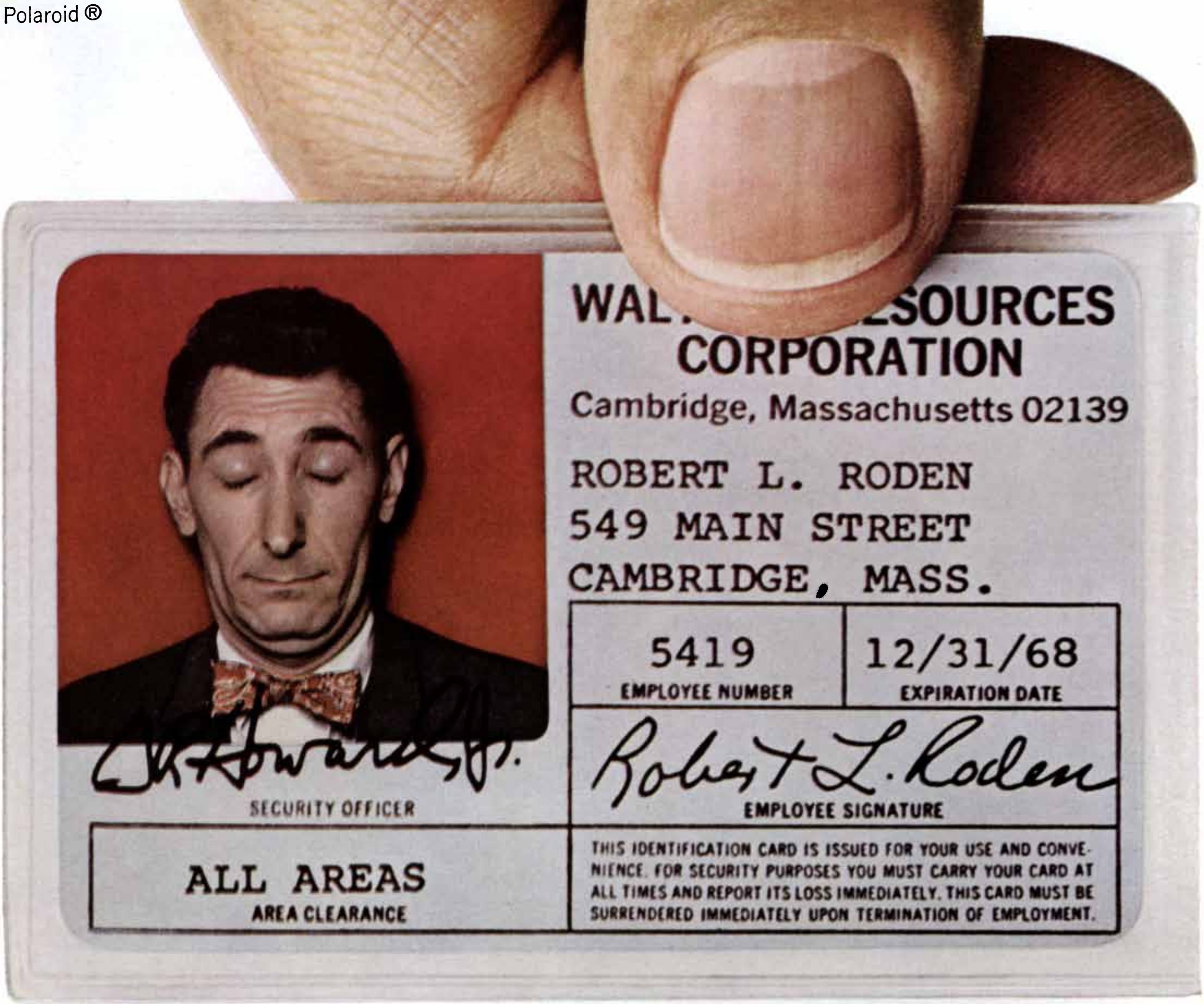

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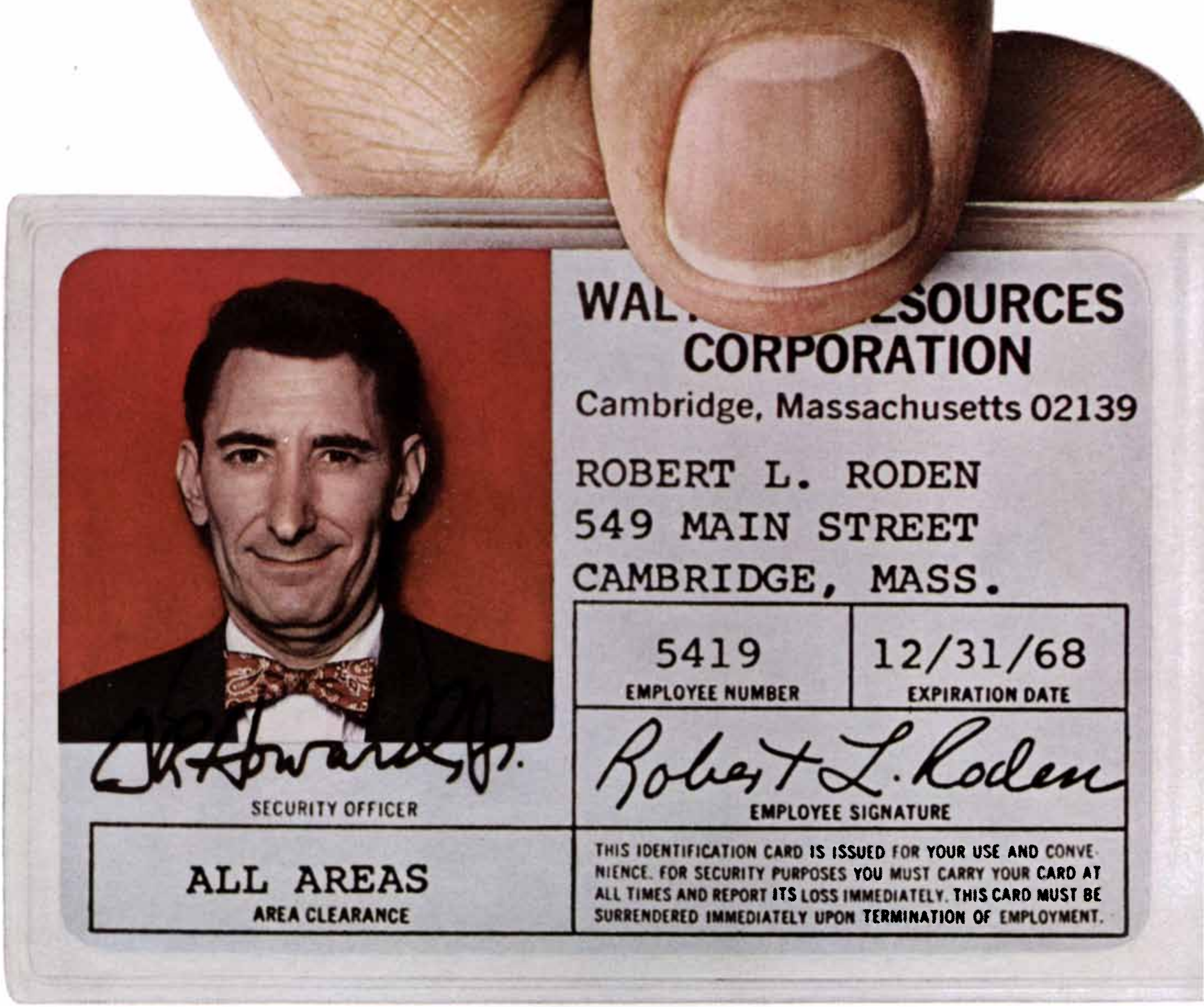

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tion studies. When we started our survey, we hoped to detect the center of the galaxy by its infrared radiation.

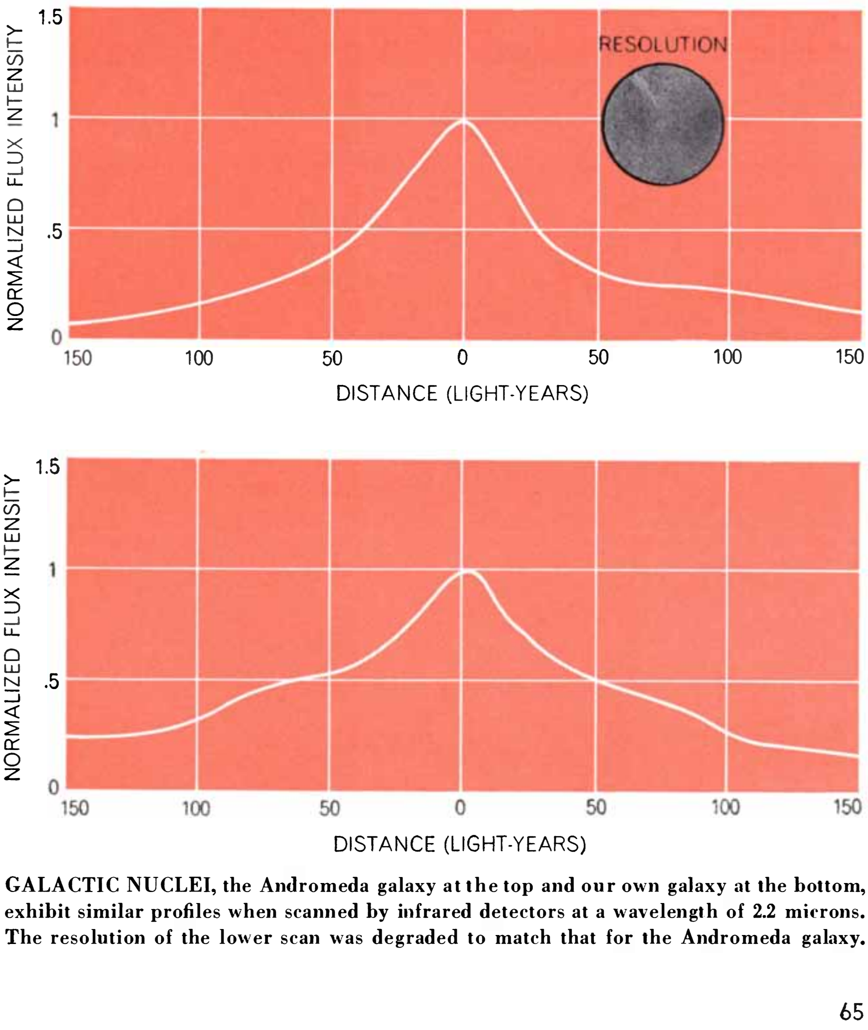
An infrared source we now believe to be the center of our galaxy did in fact show up on the survey. It was so inconspicuous, however, that we recognized it only after it had been found by Becklin with a 2.2-micron photometer on a 24-inch telescope on Mount Wilson. After this initial success further measurements were made at .9, 1.65, 2.2 and 3.4 microns using the 60-inch Mount Wilson telescope and the 200-inch telescope on Palomar Mountain. These observations reveal an extended source of infrared radiation centered on the dynamical center of the galaxy or very near it. On a larger scale a weak background is also seen, the pattern of which is quite complex [*see upper illustration on page 60*]. We currently believe most of the secondary features arise from localized changes in interstellar absorption rather than from multiple strong emitters at the galactic center. The gross appearance in the infrared agrees with radio maps of the region [*see lower illustration on page 60*].

The radiation from the galactic center can be interpreted by comparing it with radiation from the nucleus of the Great Nebula in Andromeda, which is believed to closely resemble our own galaxy. In fact, if infrared observations of our galaxy's nucleus are plotted to the same scale as infrared observations of the Andromeda galaxy's nucleus, the similarity between the two intensity profiles is striking [*see illustration at right*]. If this comparison is valid, and we believe it is, then in all likelihood the infrared radiation recorded from the center of our galaxy is produced by millions of ordinary stars densely packed into a region whose dimensions are only a few parsecs across. Inside the central core, about one parsec in diameter, the number of stars per unit volume may be about 10 million times what it is in the neighborhood of the sun. This means that the stars in the core are 200 times closer together than the stars familiar to us, so that if we lived there the stars in the sky would appear some 40,000 times (more than 11 magnitudes) brighter than those we normally see. Even so, the nearest stars would be, on the average, several thousand times more distant than Pluto, the solar system's outermost planet. As we have mentioned, the galactic center cannot be seen visually because the visible radiation from it is cut down by a factor of 10^{10}.

Close to the center of the main body of radiation there is a particularly strong infrared object that appears to be a point source. If, as seems likely, this source is located at the galactic center 10,000 parsecs away, it must be less than .1 parsec in diameter. Yet it has a total radiative output estimated to equal that of 300,000 suns. The true nature of this source is still open to debate, and no explanation put forward so far is satisfactory. Here we cannot draw an analogy between our galaxy and others because none of them is close enough for us to distinguish such a small point within the nuclear region surrounding it. If the source were a single bright star, it would be among the two or three intrinsically brightest stars ever measured. Alternatively, if it were a cluster of stars rather like the sun, the stars would have to be so close together that two of them would collide every 1,000 years or so, and the cluster would have an expected lifetime of only 1,000 million years—a span much shorter than the age of the galaxy.

The results we have described have come from observations made primarily at the near-infrared wavelengths. What would the sky look like if we used a much longer wavelength such as 20 microns? We cannot tell without an unbiased search, but perhaps a hint is given by observations of unusual objects such as quasars.

Much too faint to be detected by our survey telescope, quasars have been recently examined in the infrared both at the University of Arizona by Low and Johnson and at Cal Tech. Although measurements beyond two microns have been published for only the brightest quasar, 3C 273, it is clear that in this object and quite a few other quasars the bulk of the energy is radiated in the infrared wavelengths. Furthermore, Low and others at the University of Arizona have studied Seyfert galaxies, galaxies that have a starlike nucleus, and have found that here also the bulk of the energy is emitted in the infrared. In fact, Low finds that at least one Seyfert galaxy has its maximum emission intensity at 20 microns. How this radiation is produced is still unknown. Quite possibly it is nonthermal, meaning that the energy originates in a process entirely different from the one that produces the radiation in ordinary stars. Such results make us confident that infrared astronomy holds important clues to understanding the universe.



GALACTIC NUCLEI, the Andromeda galaxy at the top and our own galaxy at the bottom, exhibit similar profiles when scanned by infrared detectors at a wavelength of 2.2 microns. The resolution of the lower scan was degraded to match that for the Andromeda galaxy.

Experiments in Water-breathing

If the lung of an air-breathing animal (including man) is filled with the appropriate solution, the animal can obtain the oxygen necessary to sustain life. The procedure holds promise for medicine and diving

by Johannes A. Kylstra

Animal life on our planet evidently began in the sea, and it therefore started in an environment where oxygen is relatively scarce. Under the pressure of the atmosphere at sea level the air contains about 200 milliliters of oxygen per liter, but surface waters contain less than seven milliliters of dissolved oxygen per liter. This amount is equivalent to the oxygen content of the thin air at an altitude of more than 70,000 feet—where, as we know, an air-breathing mammal cannot survive.

Early forms of animal life, making the best of the conditions imposed by their aqueous environment, evolved breathing organs such as gills that are specifically designed to extract a maximal amount of oxygen from water. Eventually the evolution of lungs made it possible for animals to emerge from the sea and to benefit from the physical advantages of an oxygen-rich gaseous environment. Throughout the span of evolution, however, the function of respiratory organs has remained basically the same. In both gills and lungs, for instance, oxygen diffuses from the environment across thin membranes into the blood vessels, and carbon dioxide coming out of the blood diffuses in the opposite direction to be discharged into the environment. The basic similarity of the process in gills and lungs raises an interesting question: Could an animal with lungs "breathe" water instead of air if the water contained enough oxygen?

The question needs to be answered for several reasons. In the first place, we might learn why the respiratory organs of air-breathing and water-breathing animals are so different in structure in spite of their similarity in function. In addition, the question has a practical aspect. If by some special arrangement man could be made to breathe water instead of air, serious obstacles to attempts to penetrate deeper into the ocean and to travel in outer space might be overcome. Such considerations have prompted a number of experimental studies of water-breathing by mammals; these studies have been conducted in laboratories in the Netherlands and in the U.S.

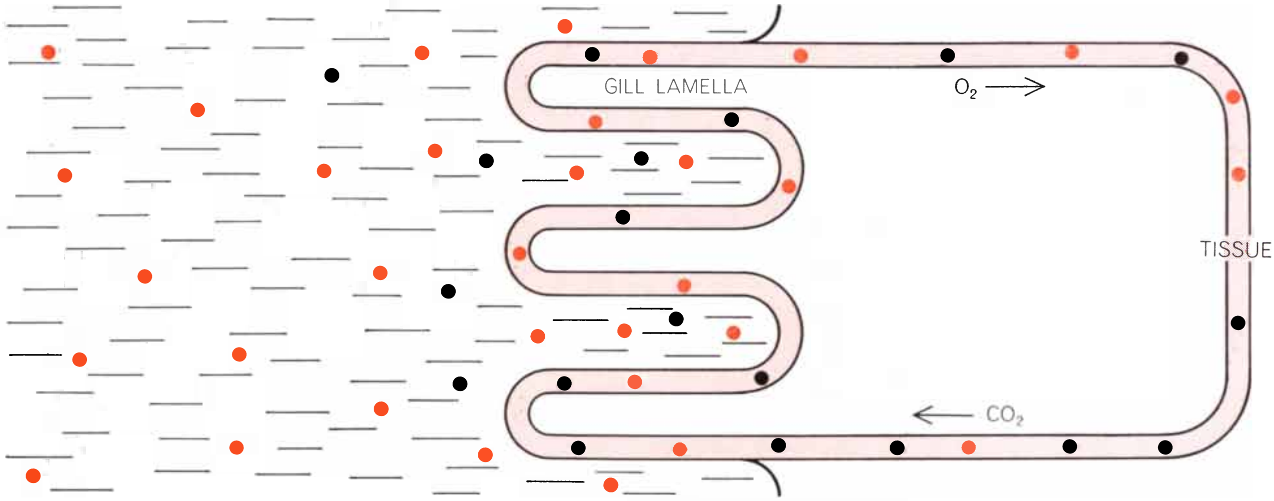
Water-breathing presents two main problems for a mammal. We have noted one: the fact that under ordinary atmospheric pressure water contains too little dissolved oxygen. The second problem lies in the fact that natural waters (fresh water or sea water) usually have a composition very different from that of blood; hence when the water is inhaled, it can damage the lung tissues and cause fatal alterations in the volume and composition of the body fluids.

Now, it is a simple matter to provide a liquid respiratory medium that overcomes both of these difficulties. Suppose we prepare an isotonic solution that is like blood plasma in salt composition and charge this solution with oxygen under greater than normal pressure. The solution's similarity to the blood will prevent any significant net change in the volume or composition of the body fluids by diffusion and osmosis. Under pressure the solution can be charged with about the same concentration of dissolved oxygen that is present in air at sea level. Can a mammal breathe such a solution?

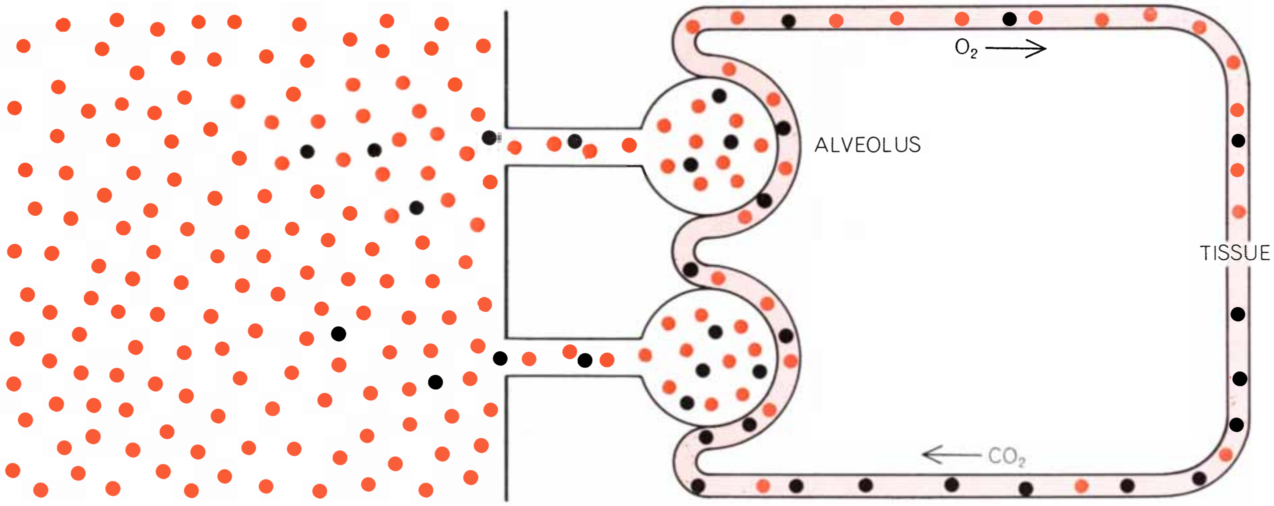
I performed the first experiments along these lines, with mice as the experimental animals, at the University of Leiden in 1961. Through a lock like the escape hatch of a submarine the mice were introduced into a pressure chamber where they were submerged in a solution such as I have just described. The chamber had transparent walls, so that the mice could be observed. In the first few moments after entering the chamber the animals tried to escape to the surface of the water, but they were prevented from doing so by a grid below the water level. After their initial agitation the mice quieted down and did not seem to be in any particular distress. They made slow, rhythmic movements of respiration, apparently inhaling and exhaling the liquid. They moved about in the chamber occasionally and would respond to a rap on the wall. Some of the mice survived for many hours, the length of survival depending on the particular conditions of the experiment (such as temperature and the chemical composition of the liquid). In each case the mouse eventually appeared to lose consciousness and ceased its respiratory activity.

From the results of experimental variations in the applied environmental conditions it became evident that the decisive factor limiting the mice's survival was not lack of oxygen (which could be supplied in ample amount simply by increasing the oxygen partial pressure in the liquid) but the difficulty of eliminating carbon dioxide at the required rate. The mouse that survived for the longest time (18 hours) was assisted by the addition to the solution of a small amount of an organic buffer, tris(hydroxymethyl)aminomethane, that minimizes the untoward effects of carbon dioxide retention in animals. Lowering the temperature of the solution to 20 degrees centigrade (about half the mouse's normal body temperature) also lengthened the survival time by cooling the animal and thus reducing its rate of metabolism.

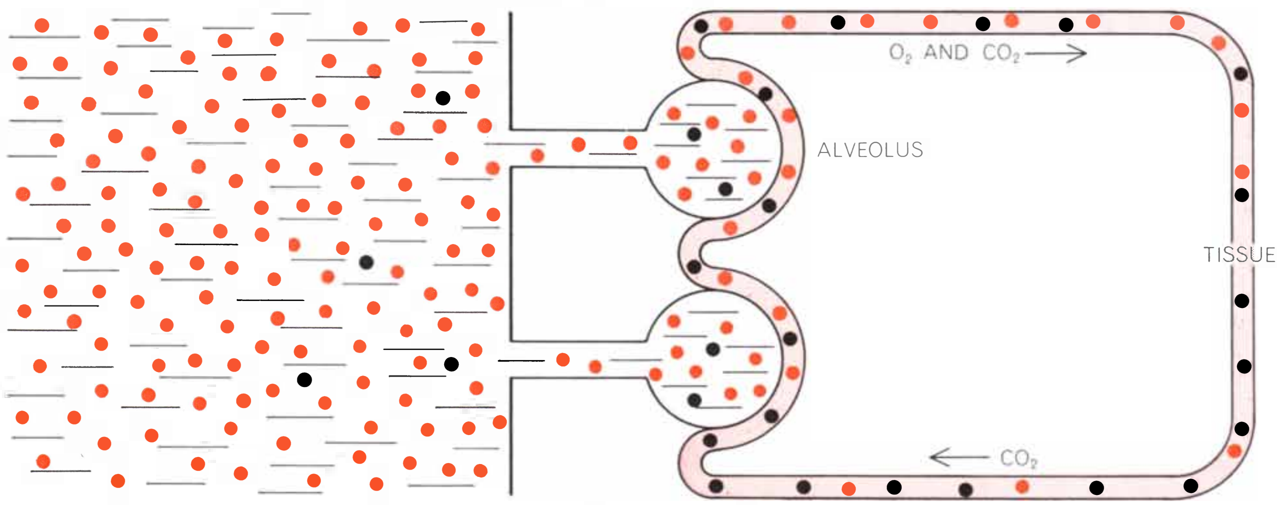
The exhaled breath of a mammal normally contains about 50 milliliters of carbon dioxide per liter. At the same temperature and carbon dioxide partial pressure a solution with the same salt concentration as blood holds only about 30 milliliters of dissolved carbon dioxide per liter. Consequently, in order to elimi-



FUNCTION OF GILL is to take oxygen (*color*) from water, which has far fewer molecules of oxygen per unit of volume than air does, and transfer it to the blood of the fish. Gills therefore consist of platelike structures called lamellae between which the oxygen-bearing water flows. Blood vessels in gills absorb the oxygen and discharge carbon dioxide (***black***), which is readily soluble in water.



FUNCTION OF LUNG is to transfer oxygen from the air, which is rich in oxygen molecules, to the blood of an air-breathing animal. The blood vessels in the lungs absorb oxygen and yield carbon dioxide by way of the alveoli, spherical structures in the lung.



WATER IN LUNG will provide enough oxygen to an animal that normally breathes air if the water has been prepared in such a way that it has a composition similar to that of blood and carries much more oxygen than water usually does. Water can be made to resemble blood in composition by the addition of salts, and the oxygen content of water can be increased by pressure. The principal problem that arises when air-breathing animals obtain oxygen from water is that they cannot discharge enough carbon dioxide.

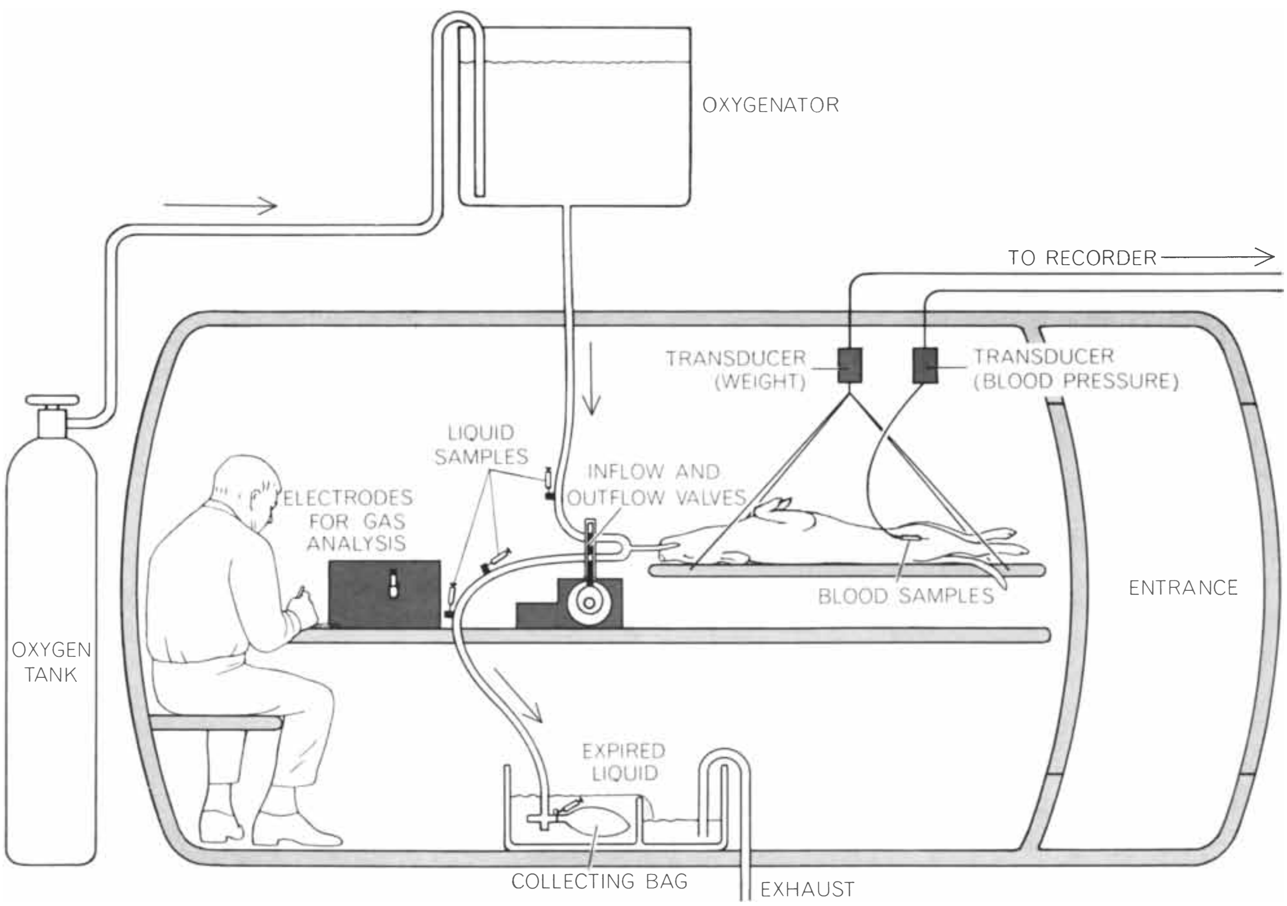
nate as much carbon dioxide via water as is eliminated via air, a water-breathing mammal would have to exhale nearly twice as large a volume of water as of air. Furthermore, it has to expel the liquid through its bronchial tubes, and that requires about 36 times more force than driving out air because the viscosity of water is 36 times greater than that of air. All of this implies that, even if turbulence did not complicate the required effort, a mouse breathing water must spend about 60 times more energy in filling and emptying its lungs than it does when it breathes air. It is no wonder that the experimental mice gradually weakened and finally gave up breathing from sheer exhaustion and the effects of retaining carbon dioxide.

The experiments with mice in a small pressure chamber did not enable us to determine how much oxygen was actually taken up by the lungs, to what extent the arterial blood was oxygenated or to what extent the animal's blood retained carbon dioxide. Consequently my associates and I proceeded to a more elaborate experiment with dogs in a large chamber provided with additional equipment. The entire chamber was pressurized with air at a pressure of five atmospheres, and the dog was lowered into a tub of saline solution that was charged with oxygen. Before the dog was submerged in the tub it was anesthetized and cooled to about 32 degrees C. (about 90 degrees Fahrenheit) in order to reduce its oxygen requirement.

During its submergence the dog made vigorous respiratory efforts, and jets of water rising from the surface showed clearly that it was pumping the solution in and out of its lungs. At the end of the experimental period the dog was lifted out of the tub and its lungs were drained of water and reinflated with air. Of six dogs tested in this series of experiments, one survived. It had breathed water for 24 minutes. The animal recovered fully and was later adopted as a mascot by the crew of the Royal Netherlands Navy submarine rescue vessel *Cerberus*.

The experiment confirmed in measurable terms that under certain conditions a mammal can indeed maintain respiration by breathing water for a limited period of time and that the principal obstacle is the accumulation of carbon dioxide in the body. During the experiment the blood pressure of the dog that survived was slightly below normal but remained stable; its heart rate and respiration were slow but regular, and its water-breathing kept the arterial blood fully saturated with oxygen. The carbon dioxide content of the blood steadily increased, however, indicating that the dog's vigorous respiratory efforts were not enough to remove sufficient amounts of carbon dioxide from the body.

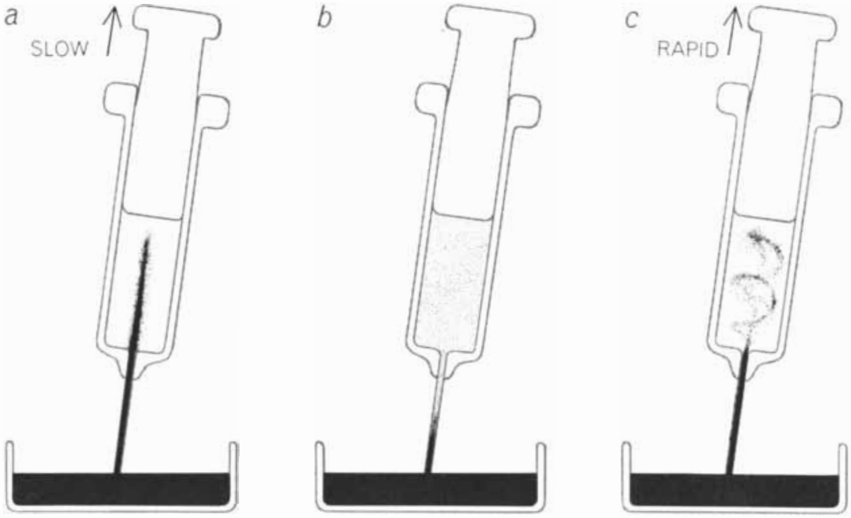
At the State University of New York at Buffalo I continued my studies together with Hermann Rahn, Edward H. Lanphier and Charles V. Paganelli, using apparatus that makes it possible to measure the actual exchange of gases taking place in the lungs of water-breathing dogs. As before, the dogs breathed a salt solution oxygenated under a pressure of five atmospheres. This time, however, we had an accurate measure of the gas content of the water they inhaled and exhaled. The oxygenated liquid was delivered to the anesthetized dog by a rubber tube inserted in its trachea, with a motor-driven valve system regulating



EXPERIMENTAL APPARATUS was used by the author and his colleagues with dogs. A dog was anesthetized, and a saline solution that had been oxygenated under pressure in a tank flowed down a tube into the animal's lungs. The dog "breathed" the solution, which then flowed by gravity into a bag. The content of oxygen and carbon dioxide in the expelled water was measured at several points.

the flow. At each inspiration the solution flowed into the lungs by gravity, and at expiration the liquid drained from the lungs by gravity into a receptacle under the dog [*see illustration on opposite page*]. The amount of oxygen taken up from the liquid in the lungs and the amount of carbon dioxide discharged into it was measured by comparing the relative amounts of these gases in the inspired and expired "breaths."

The dogs were not cooled, and we found that they extracted about the same amount of oxygen from the water as they normally would have from air. As was expected, the animals did not get rid of a sufficient amount of carbon dioxide in the exhaled water, so that the blood's content of the gas gradually increased. At the end of the period of water-breathing, which ranged up to three-quarters of an hour, the water in the dogs' lungs was drained by gravity through a hose from the trachea, and the animals' lungs were inflated with several breaths of air blown into the tube. Apart from this there was no particular resuscitation treatment. Six out of 16 dogs survived the experiments, and the six showed no ill effects.



MECHANISM OF EXCHANGE of oxygen molecules for carbon dioxide molecules in the lungs involves bulk transfer and diffusion. The same processes can be observed in a syringe that has been partly filled with water and is used to draw up ink. If the syringe is operated slowly (*a*), the ink accumulates at first along the central axis of the barrel. It then spreads homogeneously through the water by diffusion (*b*). If the syringe is operated rapidly (*c*), ink and water mix rapidly but incompletely because of turbulence. Turbulence does not occur in the gas-exchange area of a lung because the flow in that area is very slow.

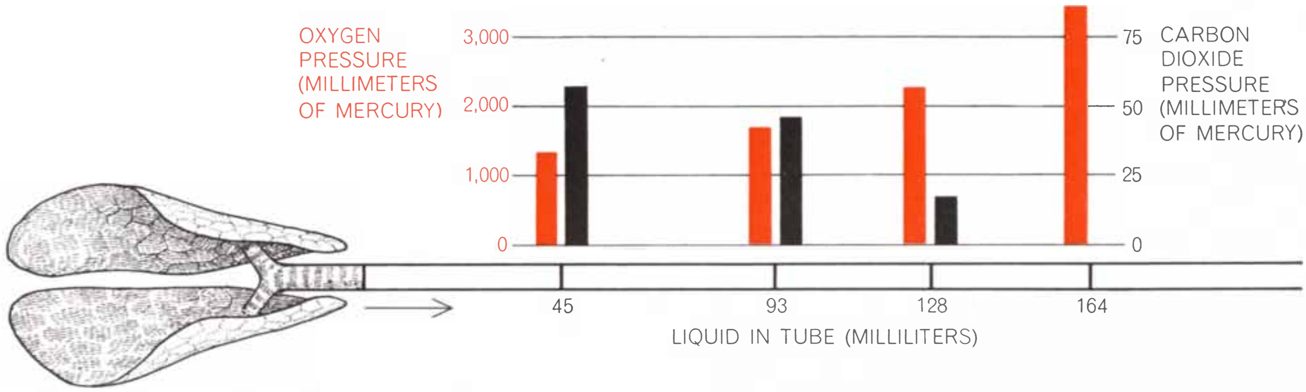
A careful analysis of the experimental data now makes it possible to describe in mathematical terms some of the factors involved in the adaptation of an animal to its environment. Respiration, both in fishes and in mammals, is based on a complex of interrelations of three elements: (1) the gas-exchange requirements of the animal, (2) the physical properties of the ambient environment and (3) the shape and structure of the respiratory organs. To penetrate beyond a merely intuitive notion of the significance of shape and structure in the adaptive process we need an exact understanding of these interrelations. A good example of the kind of question one needs to ask is: Precisely how is an oxygen molecule transferred from the environment to the blood? The answer turns out to be more complex than one might suppose.

By expanding its chest the animal takes a breath of fresh air (or water). What happens to the fluid when it is drawn into the terminal air sacs of the lungs? This can be illustrated with a syringe as a simple mechanical model. If the syringe is partly filled with water and we slowly draw in a small amount of ink through the needle, the ink initially will form a narrow stream in the center of the barrel and will be surrounded by clear water [*see illustration on this page*]. After the "inhalation" has stopped, the ink will gradually diffuse into the surrounding fluid. If the ink were drawn in rapidly, so that the flow was turbulent, the mixing of the ink and water would of course take place much more quickly. From what we know about the flow rates during inhalation by the dogs in our experiments and about the bronchial tubes' dimensions, however, we can calculate that the inhaled fluid, whether it is air or water, enters the air sacs slowly and without turbulence.

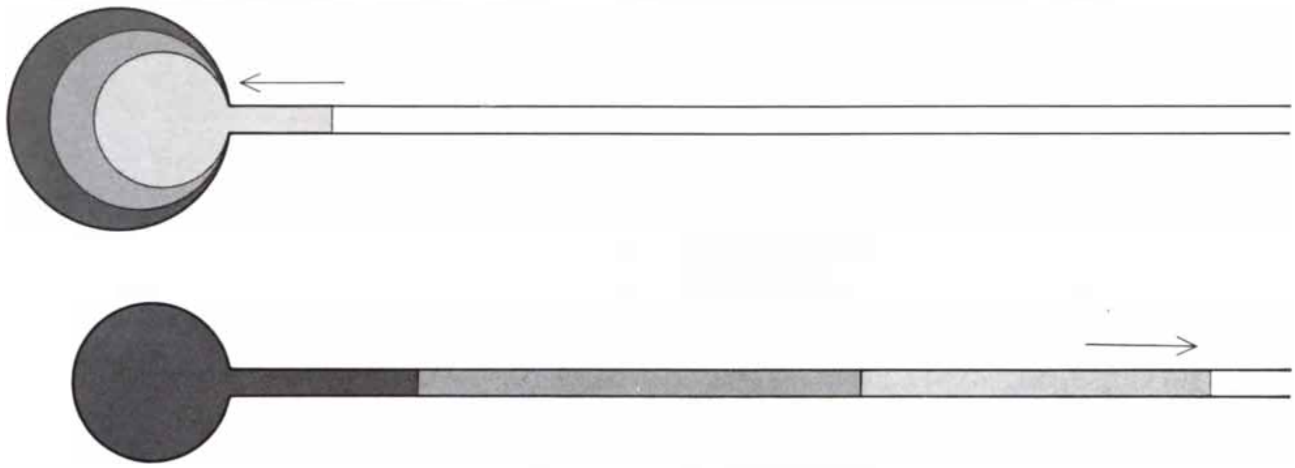
In general, then, we can assume that when a breath of fresh air or water is drawn into the air sacs, the oxygen molecules are at first concentrated in the center of the sacs and have to traverse a substantial distance by diffusion before they reach the sac walls through which they enter the bloodstream. This distance is many times greater than the thickness of the membranes that normally separate air from blood in the lung. If the breathing medium is air, this situation is of little consequence: oxygen diffuses in air so rapidly that the fresh oxygen is distributed uniformly throughout the sac within a matter of milliseconds. When the medium is water, however, in which the respiratory gases diffuse about 6,000 times more slowly than in air, the comparatively slow rate of diffusion results in a gradient of oxygen tension over the distance between the center of the sac and the walls at its periphery. Throughout the cycle of each respiration the oxygen pressure is greater at the center than at the walls. In the opposite direction the same thing is true of the carbon dioxide discharged from the blood: it is more concentrated near the transfer membrane than at the center of the sac.

These theoretical conclusions were derived from analyses of the dogs' exhalations in our experiments. When samples of the exhalations of water-breathing dogs were collected in a long tube, it was found that the first portion of the exhalation, presumably coming from the center of the air sacs, was richer in oxygen and poorer in carbon dioxide than the last part of the exhalation, presumably coming from the more distant regions near the wall of the sacs. On the other hand, similar tests on dogs breathing air showed no appreciable difference between the first and the last parts of the breath.

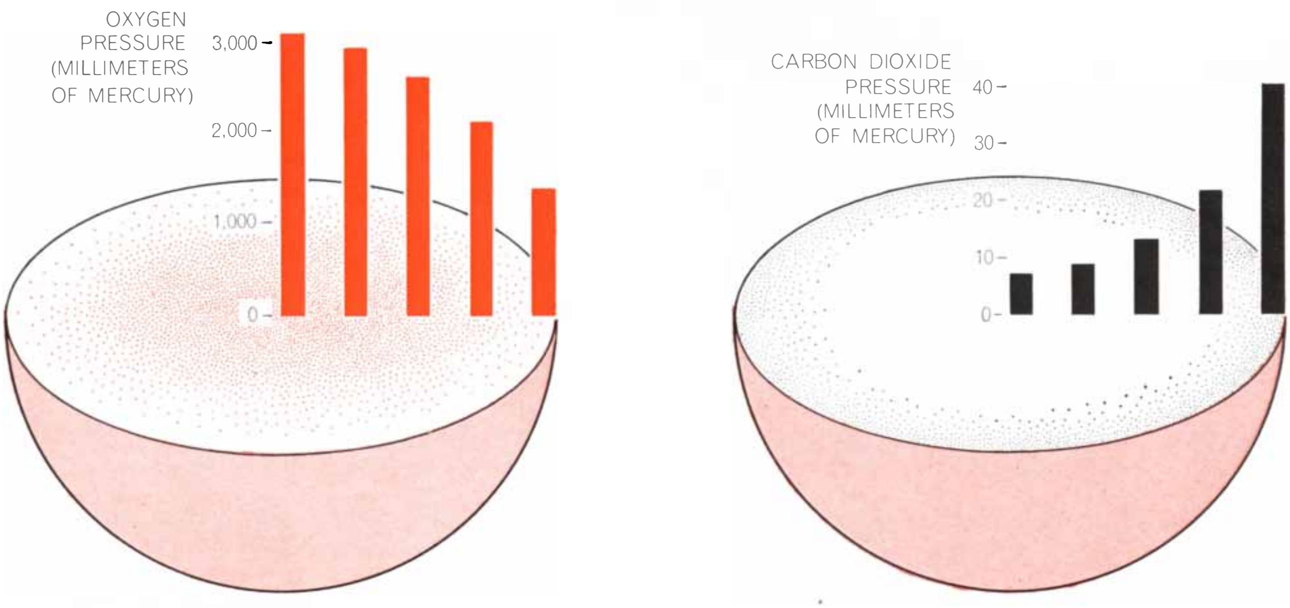
Interestingly enough, the gradients of gas tension found in the "breaths" of the water-breathing dogs turn out to be similar to those one would expect to find in a simple sphere of liquid at whose surface oxygen is exchanged for carbon dioxide. On the basis of this correspondence one can construct a mathematical model of the lung that pictures it as consisting of roughly half a million spherical gas-exchange units with a diameter of about a millimeter in which the transfer of gases occurs only by diffusion [*see upper illustration on page 71*]. The computed number and size of these units actually agree closely with the number and size of certain structures in the lung that are called "primary lobules." It seems, therefore, that these lobules may



SAMPLING PROCESS used in the experiments in the apparatus illustrated on page 68 involved determining the content of oxygen and carbon dioxide in a section of the tube carrying water discharged from the animal's lungs. Water farthest from the lungs had the largest number of oxygen molecules and the smallest number of carbon dioxide molecules. In the section nearest the lung the opposite was true. Findings led to a hypothesis, which is illustrated below, about the exchange of oxygen and carbon dioxide in the lung.



HYPOTHESIS on the exchange of gas in a primary lung lobule, or breathing unit, when an animal obtained its oxygen from water rested on the fact that oxygen and carbon dioxide diffuse 6,000 times more slowly in water than in air. As a result a lobule (*left*) shows a concentric arrangement just after an intake of water. Water in the center, having just arrived, is richest in oxygen and water near the edges is richest in carbon dioxide. On discharge the oxygen-rich water goes out first, giving rise to pattern found in sampling.



HYPOTHETICAL UNIT of gas exchange in the lung could be expected to show this distribution of oxygen and carbon dioxide if it could be sampled. Differences in gas concentration are expressed in terms of partial pressures of mercury as a gauge would show them.

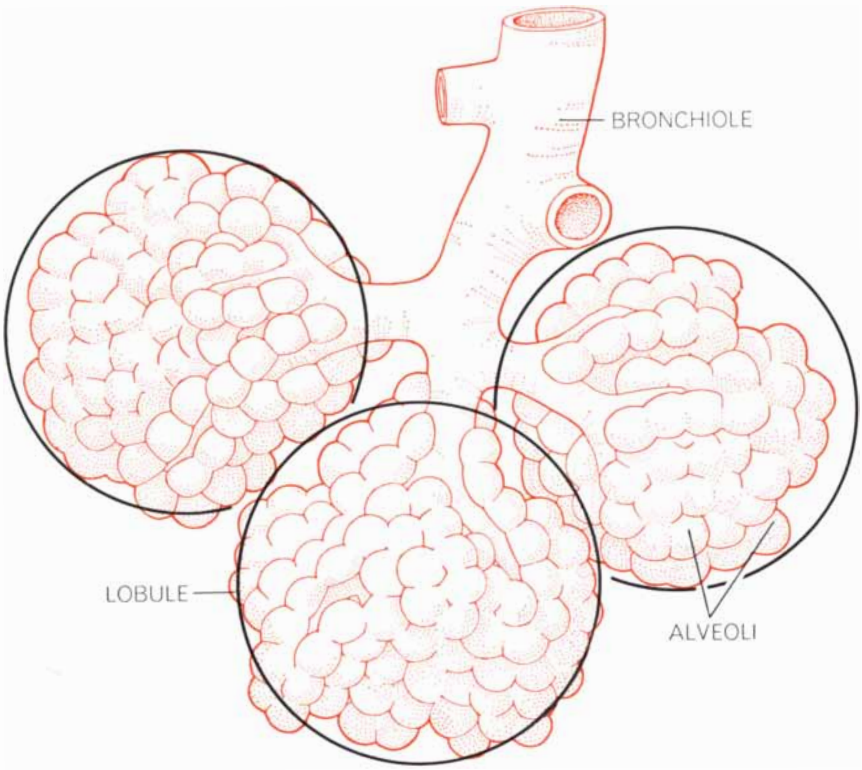
be the basic functional units of the lung. On anatomical grounds, and by analogy, one can construct a similar model for the gills of a fish in which the primary gas-exchange elements are a different shape.

The mathematical models have led us to a sharper understanding of one of the fundamental differences between the respiratory organs of the mammal and those of the fish. It turns out that the difference is essentially a matter of geometry. This becomes clear when we apply to the fish equations that relate the gas-exchange requirements of the fish and the properties of the environment to the shape of the fish's gas-exchange units. The equations take into account the availability of oxygen (its concentration, rate of diffusion and solubility in the animal's ambient environment), the volume of air or water inhaled, the number and the dimensions of the gas-exchange units, the amount of oxygen taken up by these units and the resulting oxygen tension in the arterial blood. If we apply the known values measured in a real fish to a hypothetical fish having lungs rather than gills, we find that a water-breathing fish equipped with lungs instead of gills would have no oxygen whatsoever in its blood! The fish could not exist in water. The reason would be simply that its gas-exchange units were the wrong shape. Life in the water is made possible for the fish by its thin, flat, closely packed gill lamellae—a structure that avoids the diffusion problem that makes the spherical units of the lung a liability for breathing water. In normal circumstances the only animals with lunglike organs that can survive in the water are those (such as the sea cucumber) that have a very low rate of oxygen consumption.

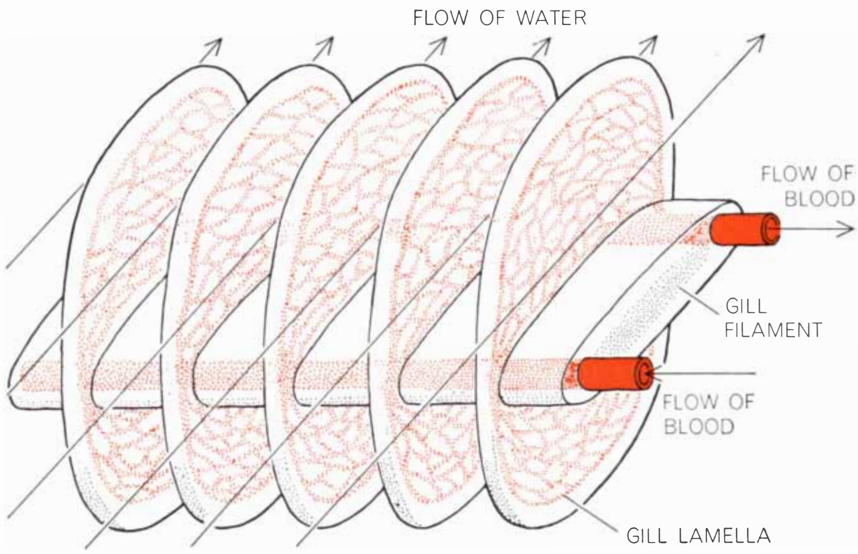
The structure of the fish's gills, which enables the fish to live in the water, is also largely responsible for its inability to live out of the water. In the air these delicate structures tend to collapse under the pull of gravity. Moreover, the surface tension at the interface of air and water causes the closely packed gill lamellae to stick together. Consequently the total gill area available for gas exchange is so greatly reduced that the fish's respiration fails in spite of the abundance of oxygen in the air. In air-breathing lungs the air sacs likewise would collapse were it not for two factors that hold them open. One is the chest's pull on the air sacs; the other is the lungs' secretion of a wetting agent that minimizes the surface tension at the moist surfaces of the lung structures.

The research on water-breathing in mammals has thus shed considerable light on some of the basic principles of the breathing process. On the practical side the findings suggest that man might indeed breathe water for limited periods without harm. This would enable divers to go down to considerably greater depths in the ocean than they can at present.

The chief hazard in deep diving is the compression of the air in the lungs by the pressure on the chest from the weight of the overlying water. The pressure forces gases in the lungs into solu-



PRIMARY LUNG LOBULES, three of which are indicated by the black circles, appear to be the basic functional units of the lung. Each has a large number of alveoli, where the exchanges of gas between air or water and the blood take place. The number and size of primary lung lobules agree closely with a mathematical lung model, consisting of about 500,000 spherical units, derived from gas-exchange results measured in water-breathing dogs.

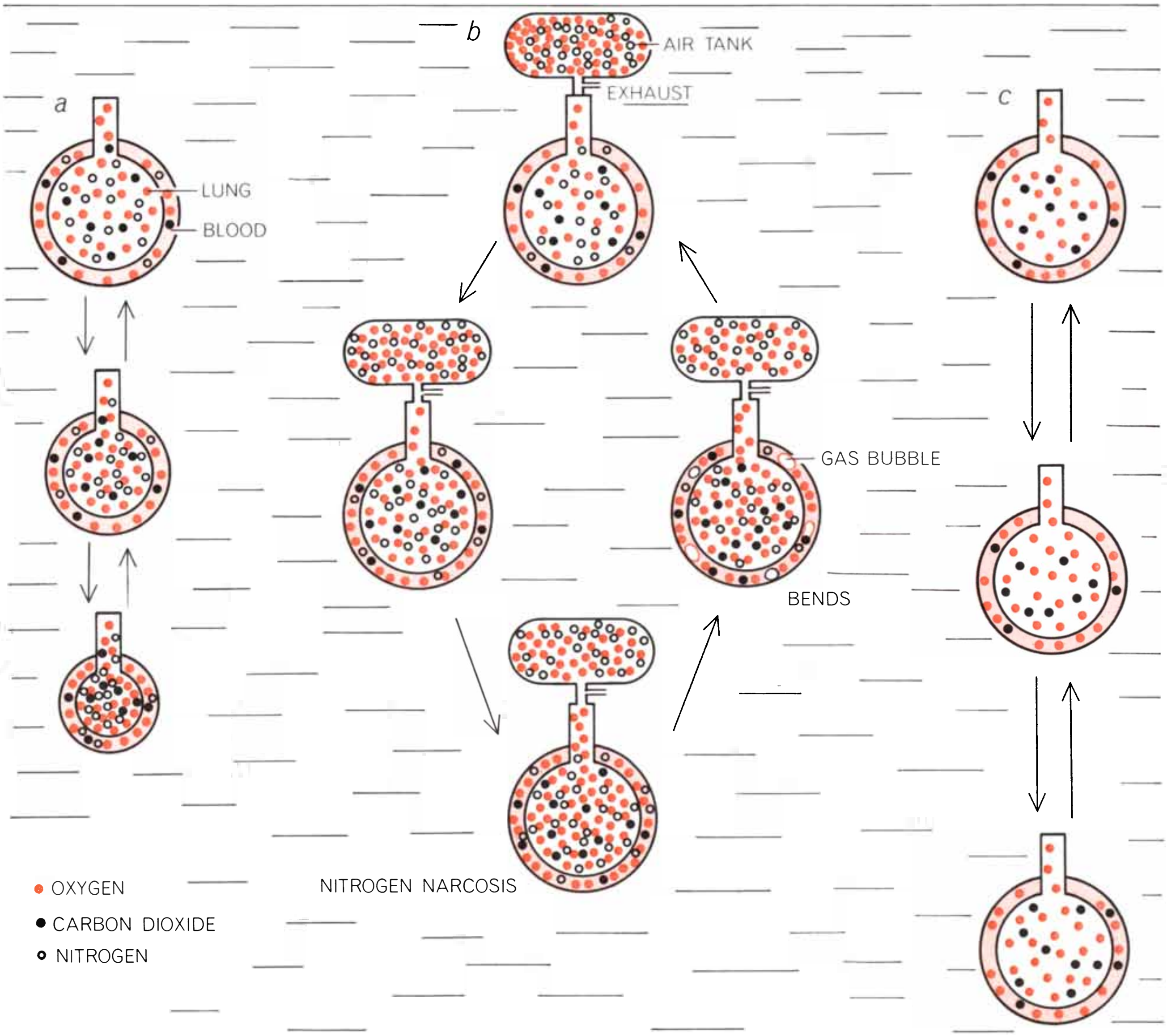


GILL STRUCTURE consists of a large number of flat, parallel planes in which gases are exchanged between water and blood by diffusion. A hypothetical fish with spherical gas-exchange units, such as those shown in the upper illustration on this page, would not survive because gases diffuse so much more slowly in a sphere than they do in a plane structure.

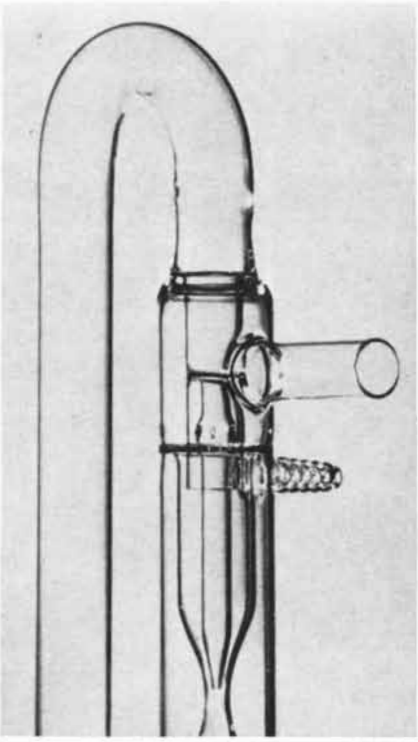
tion in the blood, with two serious consequences. At heightened concentrations in the blood and tissues most gases are toxic; the nitrogen forced into the blood of an air-breathing diver, for instance, begins to produce a state of intoxication at a depth of 100 feet and incapacitates the diver by nitrogen narcosis at about 300 feet. (This problem can be solved by the use of rare gases, such as helium, that are not narcotic at very high partial pressures.) Secondly, if a diver returns too rapidly to the surface from a deep dive, the gases dissolved in the blood and the tissues are released as bubbles, thereby producing decompression sickness, known as "the bends." This hazard can be eliminated by having the diver breathe a liquid instead of air, since liquid in his lungs would resist the external pressure without significantly changing in volume. By breathing a suitable liquid enriched in oxygen a diver might descend to depths of several thousands of feet and return rapidly to the surface without harm.

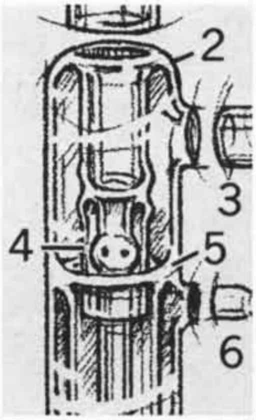
That the bends can in fact be prevented by this means has recently been demonstrated by experiments with mice in my laboratory at the Duke University Medical Center. We have decompressed a liquid-breathing mouse from a pressure of 30 atmospheres to normal atmospheric pressure within three seconds without causing any observable ill effects in the animal. This rate of decompression is equivalent to rising from a depth of 3,000 feet under water to the surface at a speed of 700 miles per hour.

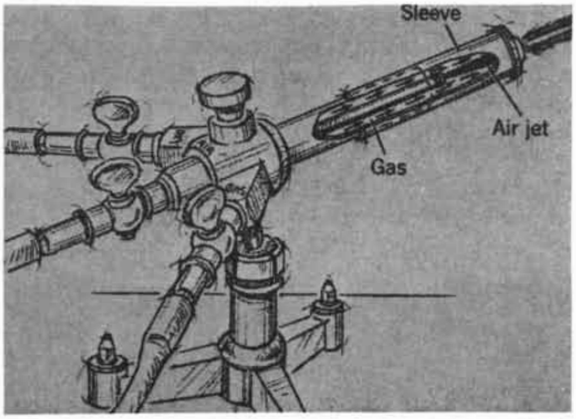
Liquid breathing might also serve a purpose in man's future ventures into space. In a journey to a large planet such as Jupiter, for example, the escape from the planet's gravitational attraction for the return trip would require an enormous acceleration, much greater than a man's body (particularly the vulnerable lungs) could withstand. Such an acceleration could be tolerated, however, if the lungs were filled with liquid and

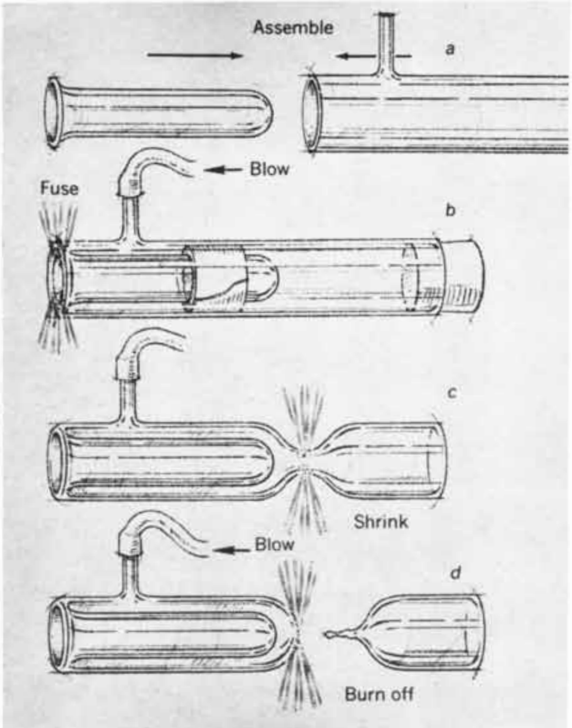


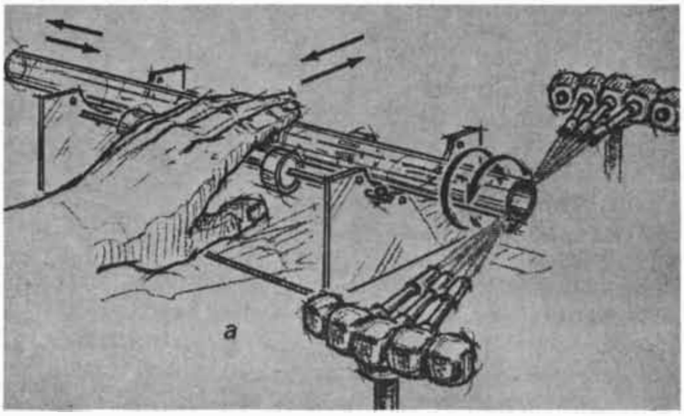
AID TO DIVERS would result from the use of oxygen-rich water instead of air in the lungs. When a skin diver holds his breath (*a*), air in his lungs is compressed as he dives, and some gas is forced into solution in his blood. A scuba diver who breathes air from a tank (*b*) can go deeper because the volume of his chest does not diminish, but more gas is dissolved in his blood and tissues. If he goes deeper than about 300 feet, the concentration of nitrogen in his brain becomes so high that it produces nitrogen narcosis. If he rises too rapidly, the dissolved gas is released as bubbles and he suffers "bends." A diver with water in his lungs (*c*) would not have these problems, because water is virtually incompressible. Air contains 80 percent nitrogen; oxygen ratio is increased here for emphasis.











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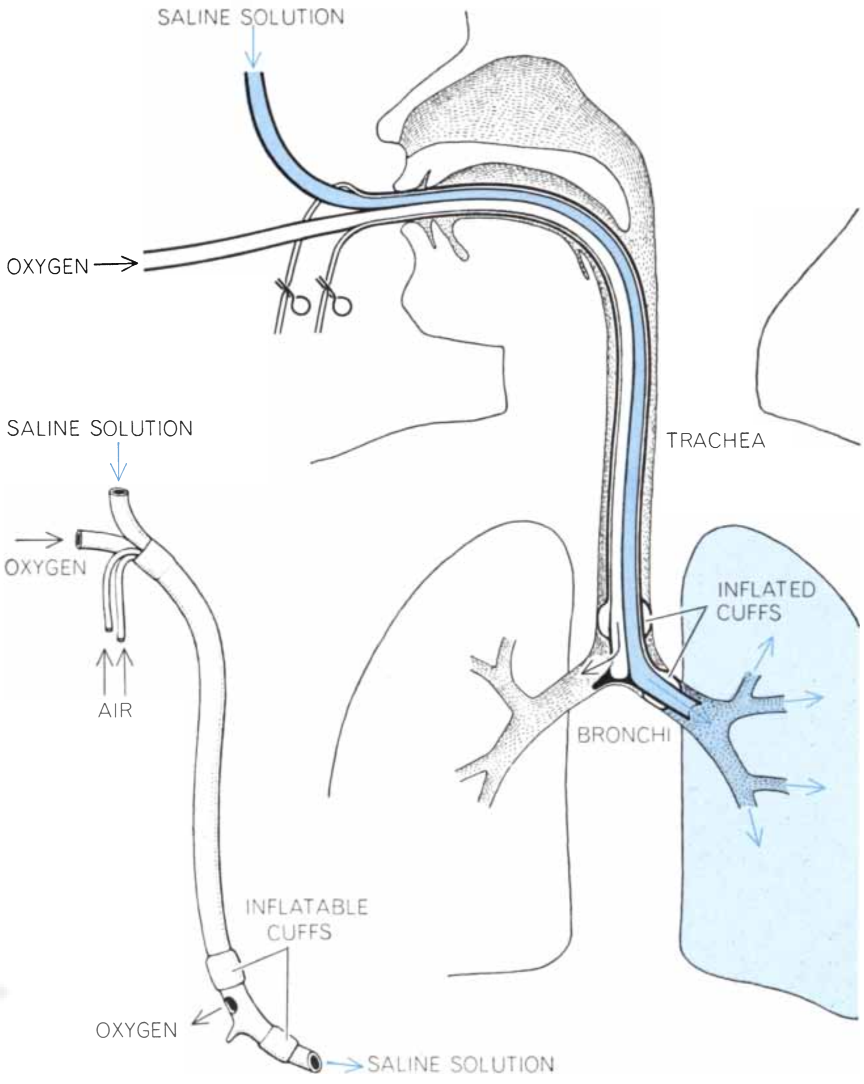
the body were suspended in a liquid with the density of blood—like a fetus in the amniotic fluid of the mother's womb. The Italian physiologists Rodolfo Margaria, T. Gualtierotti and D. Spinelli demonstrated the validity of such an idea in 1958. They placed pregnant rats in a steel cylinder and dropped the cylinder on a lead pad to see if the fetuses could survive the impact of the deceleration on landing. The cylinder was dropped from various heights, and the deceleration was computed from the depth of the indentation the cylinder made in the pad. The animals themselves died instantly, and autopsies showed that their lungs had suffered extensive damage. Their fetuses, however, delivered surgically after the fall, lived through the experience and developed normally. The fetus, cushioned by the fluid in the womb, was able to survive decelerations up to 10,000 *g*'s.

It seems reasonable to suppose that the water-breathing capabilities shown by other animals would be shared by man. Indeed, we already have some rather direct evidence on this question. At the Duke Medical Center we use a new method of treating certain lung disorders that is called lung lavage. The method consists of washing the lungs, one at a time, with a saline solution to remove pathological secretions from the air sacs and bronchi. While one lung is being rinsed, the other breathes gaseous oxygen [*see illustration below*]. The fact that this operation can be conducted successfully encouraged us to try an experiment for which a courageous deep-sea diver, Francis J. Falejczyk, volunteered. His windpipe was anesthetized and a double-tubed catheter was inserted through it, one tube going to each lung. The air in one lung was replaced by a .9 percent saline solution at normal body temperature. A "breathing" process consisting of adding more saline solution to the lung and draining an equal amount was then repeated seven times, with 500 milliliters of solution used for each "breath." Falejczyk, who remained fully conscious during the procedure, told us afterward that the liquid-filled lung had not felt noticeably different from the gas-filled one and that he had had no unpleasant sensations from the flow of liquid into and out of the lung. Of course this test was very different from trying to breathe water with both lungs, but it did show at least that filling the human lung with a saline solution will not seriously damage the tissues or produce unacceptably disagreeable sensations if it is done properly.



LAVAGE OF LUNG is a clinical procedure whereby a liquid of suitable composition is put into a lung to wash out of the respiratory system material that the patient cannot expel naturally. By means of a tube arrangement shown both in the trachea and at lower left, oxygen is put into one lung and saline solution into the other one. The patient breathes only with the lung receiving oxygen; the sole function of the liquid in the other lung is rinsing.

Probably the most difficult problem that will have to be solved is the matter of the elimination of carbon dioxide. Removal of carbon dioxide from the lungs by way of water would require a considerably greater expiratory rate than in the case of removal by way of air. Yet, since water is roughly 40 times more viscous than air, the lungs' capacity for expelling water is at best no more than a fortieth of that for air; in other words, a healthy young diver capable of breathing 200 liters of air per minute could breathe only about five liters of water per minute. It is certain that a water-breathing diver could not possibly eliminate carbon dioxide at the necessary rate, even if he were absolutely at rest in the water.

Could the problem be solved by using a liquid in which carbon dioxide dissolves more readily than it does in water? There are such liquids: some synthetic fluorocarbons in liquid form, for example, can dissolve about three times as much carbon dioxide, and about 30 times as much oxygen, as water can. Leland C. Clark, Jr., of the University of Alabama Medical Center and Frank Gollan of the Veterans Administration Hospital in Coral Gables, Fla., have kept cooled mice alive in a fluorocarbon liquid containing oxygen under normal atmospheric pressure. This liquid not only holds more oxygen but also provides the advantage of allowing oxygen to diffuse four times more rapidly than it does in water. The slow rate of expiration of the liquid from the lungs still remains a stumbling block; in fact, fluorocarbon liquids are more viscous than saline water is.

By 1978, cars will be less of a smog

Some people think of the twenties as the golden age of motoring. They have a point.

We drove on wiggly roads instead of turnpikes. Fifty miles an hour was heady stuff. Cars were reasonably reliable but still slightly adventurous. And there weren't many of them. Who cared if they smoked a bit? The blue vapors floated up to the blue sky and disappeared. Or seemed to.

By the fifties, things were different. There were twice as many cars. And a new word had entered our vocabulary. Smog. The car's contribution to this phenomenon had become a problem to be taken very seriously. Rightly so.

By 1978, there will be six times as many cars on American roads as there were in the late twenties. Will the exhaust problem be six times worse? The answer from Jersey's affiliate, Esso Research, is a resounding no. Here are a few incontrovertible facts.

Air pollution from cars reached its zenith last year. We have now passed the turning point. Despite the car population explosion, total exhaust emissions will go down this year—further down in 1969—and further and further down in all successive years.

problem than they were in 1928.

By the early eighties, the unburned gasoline exuded by each car will be less than half an ounce a day. Little more than you need to fill a cigarette lighter.

Credit for this encouraging news must go equally to oil industry scientists, automotive engineers and intelligent lawmakers. But Jersey can justly claim a major role.

Esso Research scientists have worked with car experts to design fuels and lubricants that help cut unburned gasoline vapors and carbon monoxide to a minimum.

They have built a simple device that can reduce evaporation from your gas tank and carburetor by 95 per cent.

And they are now studying catalysts and other systems that will actually change pollutants into nonpollutants.

Ten years from now, we may well look back on the 1960's as the not-so-golden age of smog.

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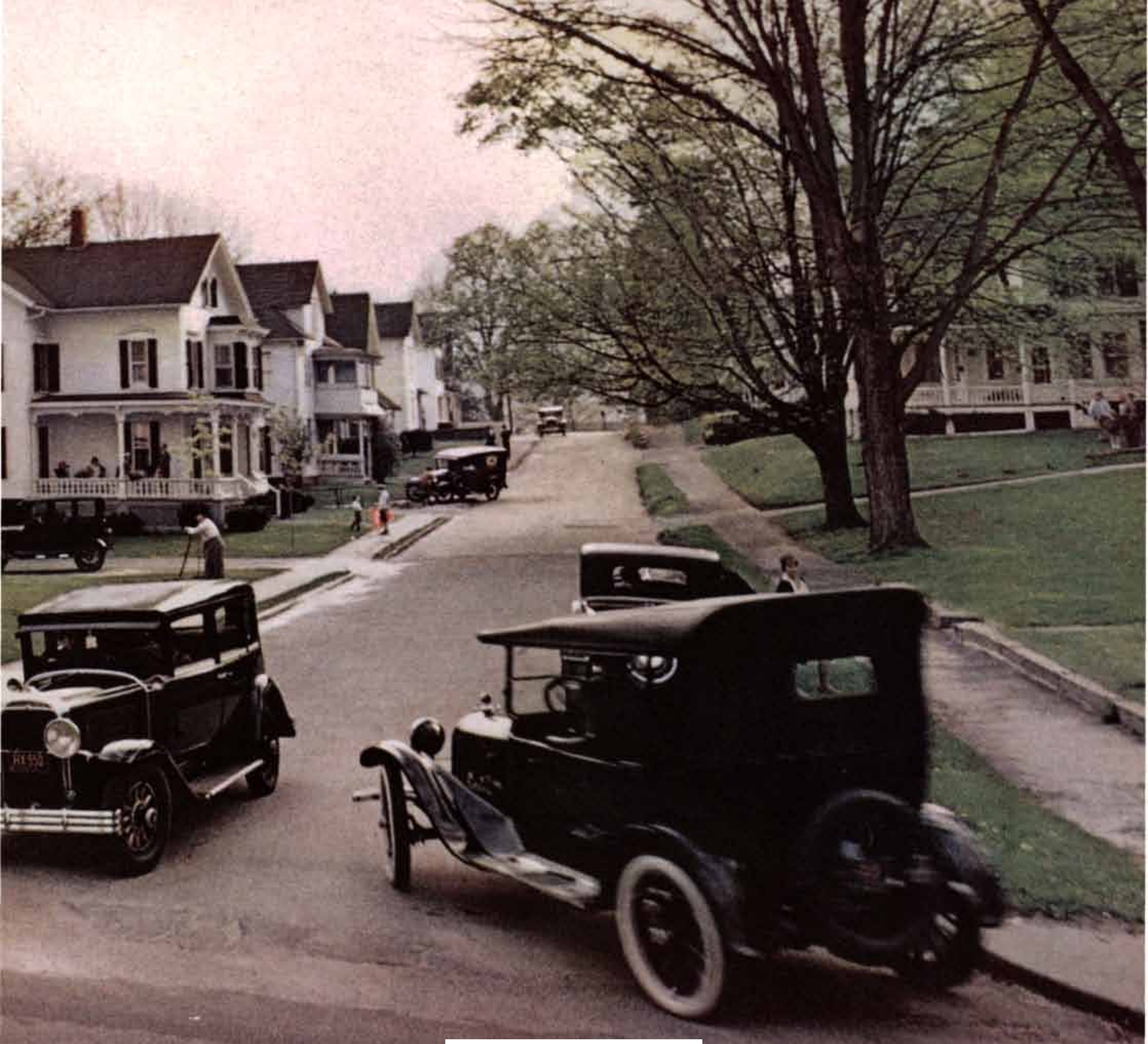
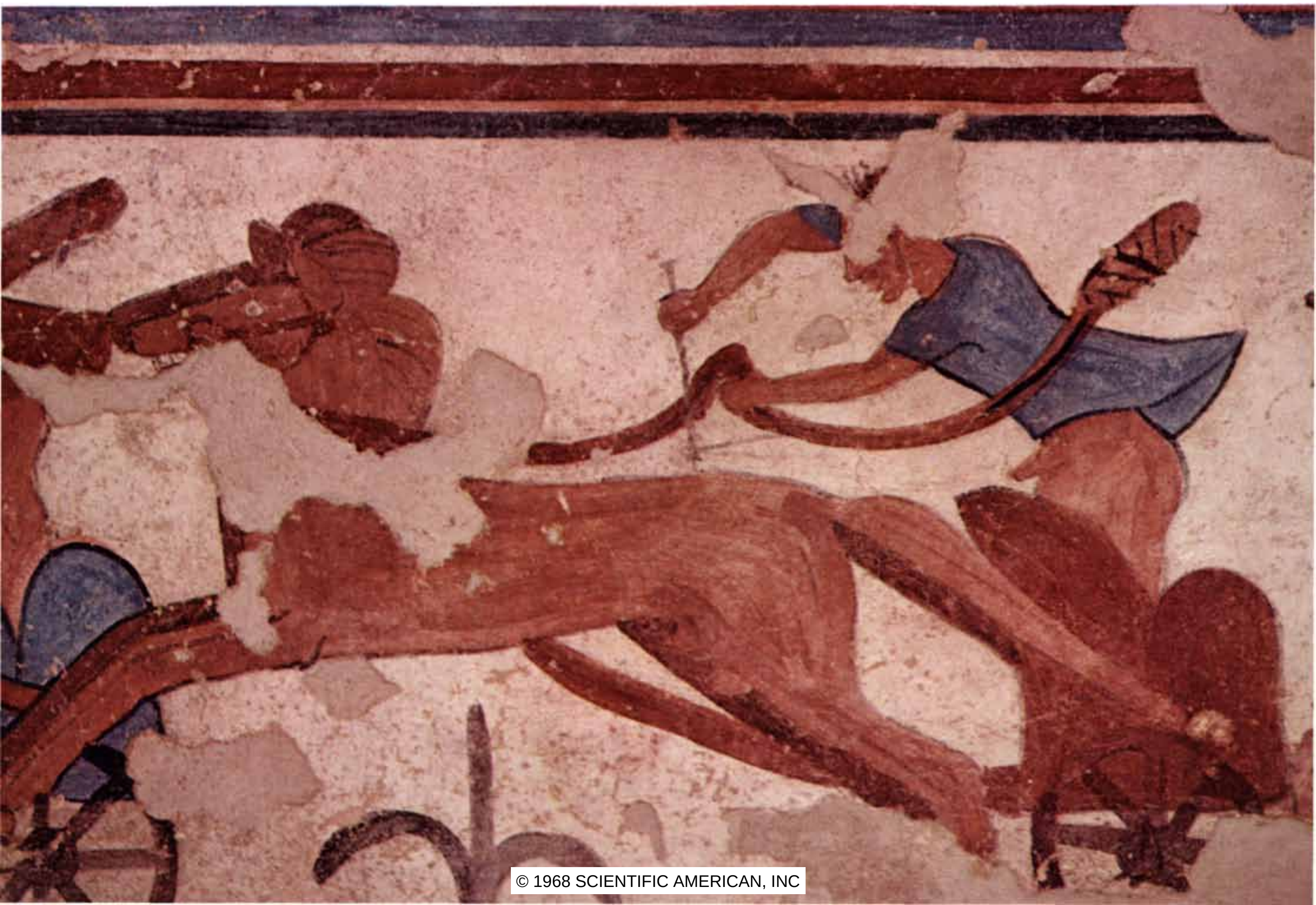




The Origins of the Olympic Games

Competitive sports had roots in religion, mythology and military training and were nurtured by the Greek passion for excellence. Many of today's events were accurately described in the Iliad

by Raymond Bloch

Ancient Greece can truly be considered the birthplace of competitive sports as we know them. The origins of such sports go back several thousand years. Long before the first Olympic games were staged at Olympia in 776 B.C. the Greek people had developed a taste for sports that elevated athletic games to a prominent place in their ceremonial life and the education of the young. Sporting contests of those early times are glorified in Homer's *Iliad*. In general, the Greek literature of antiquity suggests that sports enjoyed a popularity very much like that in our own day, and that then as now champion athletes were taken to the hearts of the people more enthusiastically than philosophers or statesmen.

The history of sport as an absorbing human activity surely merits more scholarly study than it has had. It has seemed to me that it would be of considerable interest to examine the development of this activity in ancient Greece, comparing the games, styles, performances and rewards with those of today. For such a study one must of course depend on the same kinds of source that one consults in any investigation of ancient history: one intensively combs the surviving literature of the time, surveys and interprets relevant inscriptions on various preserved objects and examines in detail the remains of pictorial representations of the activity in question. The task of assembling specific data on the sports of that distant time turned out to be more difficult than I had supposed it would be. For example, we have very little information about the performances of the Greek champions, such as the times they achieved in running races; the ancients had no instruments for the precise measurement of time. From literary descriptions, pictures, sculptures and other materials, however, it proved to be possible to learn many details about the popular games and exercises, the manner and spirit in which they were performed, the attitudes toward sports and the evolution of sports activities from the early Homeric period on through the Greek, Etruscan and Roman eras.

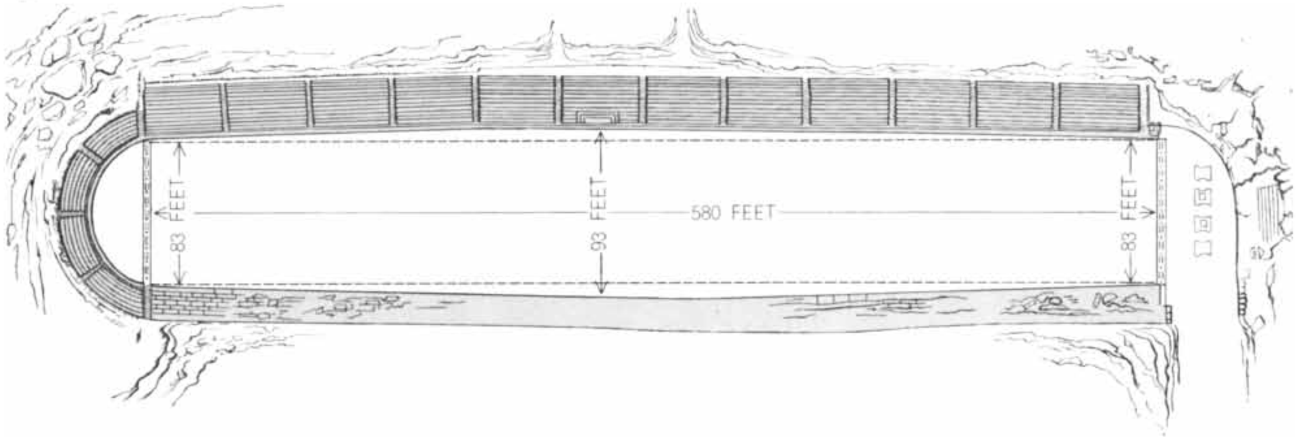
Sports competitions among the Greeks began with a religious orientation, as is still the case among many primitive peoples today. Contests of physical strength and skill were believed to invigorate and renew the youth of the participants, to activate the powers of the gods and, by inspiration, to restore to the dead (living a pale reflection of life underground) some of their lost powers. Funeral ceremonies were therefore featured by athletic games (a practice that persisted to Roman times, as Virgil's *Aeneid* indicates). The Greeks soon developed rational foundations for their games, however. As philosophers and as warriors they came to cultivate physical exercise for its health-giving value and its preparation for combat—or as a peaceful alternative to combat.

Above all, sports had a special appeal for the Greek people because of their singular philosophy and life ideal. The cornerstones of this philosophy were the love of perfection and of beauty—beauty of both mind and body. With an intense desire to approach the ideal of a well-rounded man they made gymnastics and athletics a central part of their system of education of children. The urge to perfection also instilled in the Greeks an incandescent desire for victory in every endeavor. These elements of their philosophy and character go far to explain not only the Greeks' extraordinary interest in competitive sports but also the spirit with which they approached games. The goal was always victory—at any cost.

The essence of their attitude and the manner in which sporting contests were conducted are well illustrated in one of the earliest accounts of such an exhibition, related in Book XXIII of the *Iliad*. As a funeral tribute to young Patroclus, who had fallen in combat, Achilles organized a set of games on the plain before the ramparts of Troy. The participants and the spectators were soldiers, and naturally the principal event was a chariot race. Achilles fired the contestants with attractive prizes: for the winner, a woman to take home who was skilled in fine crafts, plus a handsome 22-pint vessel with ear-shaped handles; for the runner-up, a pregnant mare, and for the third, fourth and fifth places, objects of somewhat lesser value.

Homer sets the stage with a lengthy lecture by Nestor to his son Antilochus, one of the contestants, before the race. The lecture reveals the high importance the Greeks attached to the role of intelligence in all affairs, even physical contests. The race would not go necessarily to the swiftest horses but to the driver who exercised the most careful thought and surest wisdom. Nestor coaches his son in detail on how to han-

TWO CLASSIC EVENTS, the discus throw and the chariot race, are depicted in the frescoes reproduced on the opposite page, which date from about 525 B.C. They decorated the wall of a tomb unearthed 10 years ago in the burial ground of the Etruscan city of Tarquinia, northwest of Rome. The Etruscans, who occupied much of the Italian peninsula before they gave way to the rising power of Rome, had extensive trade and cultural contacts with Greece.



STADIUM AT DELPHI, the ruins of which are diagrammed here, was rebuilt in the second century A.D. with tiers of seats, many of which remain. At most earlier stadia, including the one at Olympia, the spectators took their places on hillsides surrounding the running field. The starting and finish lines were marked by stone slabs. The sides of the stadium were curved gently for better visibility.

dle the horses and make his moves, remarking: "It is skill rather than brawn that makes the best lumberman; it is skill that enables the steersman to guide his wind-tossed ship over the wine-dark sea; it is skill that makes one chariot driver prevail over another. One man will leave too much to his chariot and pair, letting them wander hither and yon over the track, foolishly letting them make a wide turn. Another may be driving mediocre horses, but he always keeps his eye on the [turning] post and he wheels close in; he does not forget to hold his beasts firmly by the oxhide reins and he watches the man ahead of him." It is perhaps not without significance that in his lengthy exhortation to his son on how to run the race Nestor says nothing about fair play toward the opponents. As the race itself shows, the Greeks were so concerned with finesse and victory in competitions that they sometimes forgot the demands of true sportsmanship.

The five contestants line up in their war chariots, each drawn by two racehorses, in an order that has been decided by lot. On signal they start toward a distant turning post that they must round before returning to the starting line. Homer describes the race with technical exactitude, with emotion, with humor and with perceptive attention to the contestants, their horses and the audience. The poet treats of the horses as if they were human, animated like their drivers with fear of losing and a burning desire to win. Antilochus addresses his horses in this vein: "Why have you let yourselves be outdistanced, my braves? Give heed to me.... Do not expect that

FOOTRACE, apparently a sprint, is shown on an Athenian storage jar that dates from about 530 B.C. Olympic contestants generally wore nothing but a coating of oil. The arm motion is unnatural here (left arm forward with left leg), presumably for aesthetic reasons.

Nestor, the shepherd of men, will treat you with mercy. He will slit your throats without hesitation if you slacken and come in for only a trivial prize. So after them, full tilt!" Homer goes on: "The horses were seized with fear at the scolding voice of the master and increased their pace forthwith."

In his passionate desire to win impetuous Antilochus crowds the chariot ahead of him and forces it to give way to avoid a collision. For this the young man is criticized after the race by Menelaus, but Homer apparently does not consider the offense to be grounds for disqualification, as it would be in a horse race today.

The soldiers who form the audience, being themselves practiced in chariot driving, follow the race as connoisseurs with a keen appreciation of the fine points. Their emotional involvement also is high, and Homer records the crowd's reactions with the vividness and excitement of a present-day sportscaster. Disputes and altercations arise among the spectators just as they do in grandstands today. Looking across the plain at the distant charioteers veiled in dust, fiery Ajax engages in a fierce argument with Idomeneus, the elderly Cretan chief, about who is winning. Ajax insists that Eumelus is in the lead; Idomeneus argues that the leader and probable winner is Diomedes. Idomeneus turns out to be right.

The race is actually decided by the gods, who exhibit lapses in sportsmanship like those of mortal men. Apollo, who favors Eumelus, causes Diomedes to lose his whip. Thereupon Diomedes' partisan, Athena, comes to the aid of her man by firing his horses to greater efforts and breaking the yoke holding Eumelus' horses to the shaft. The horses swerve away, the shaft falls to the ground and Eumelus is thrown from the chariot. Diomedes sweeps on to victory. Evidently Homer, like other ancient writers, took this means of paying ultimate homage to the gods; even skill and intelligence were not enough when the gods chose to intervene in behalf of their favorites.

A striking aspect of Homer's account of this great meet staged by Achilles is the degree of involvement of all concerned, spectators as well as contestants. In a sense the spectators were participants—at least potential participants—in the events. This was in sharp contrast to the later development of sports in imperial Rome. The Roman audiences came to see a spectacle performed by professionals—a spectacle that was unrelated to the experience of the spectators. They were merely passive onlookers at an exhibition. The contests aroused them to excitement and emotional involvement, to be sure, but the Roman spectators, unlike the Greeks, had little interest in the personal practice of sports and exercises for their own sake or in the educational ideal of a harmonious development of mind and body.

ATHLETES PRACTICING for three Olympic events are depicted on this Athenian vase dating from 525 to 500 B.C. The man at the left is hefting the *halteres*, weights utilized in the long jump. The javelin-thrower (*center*) is balancing his light lance as he runs toward the throwing line. The discus-thrower (*right*) is in the stance that precedes the windup.

Homer goes on to describe other sports that were included in Achilles' meet: boxing, wrestling, footraces, archery and combat with weapons. For the boxing match Achilles offers two prizes—a mule to the winner, a two-handled mug to the loser—and invites contestants to volunteer. Epeius, a champion boxer, comes forward and his challenge is accepted by Euryalus. Epeius cries out: "With one mighty blow I will tear this fellow's flesh to ribbons. Let his mourners gather around and be ready to carry him away when I have finished with him." The threat is not mere boastful hyperbole. Boxing in ancient times was an extremely dangerous sport that not infrequently meant death for the loser. The Greeks did not use the barbaric cestus loaded with lead or iron that was later adopted by Roman boxers, but the oxhide bindings with which they covered their fists were still murderous. The boxer aimed all his blows at his opponent's face and head, which explains why the ancient fighters, unlike boxers today, seem always to have had their arms raised. Because boxers did not fight in weight classes, small men tended to avoid this sport; the boxers of ancient times were generally heavy men who continually stuffed themselves with food to prepare for their contests. The combat went on without interruption until one of the boxers was totally unable to continue.

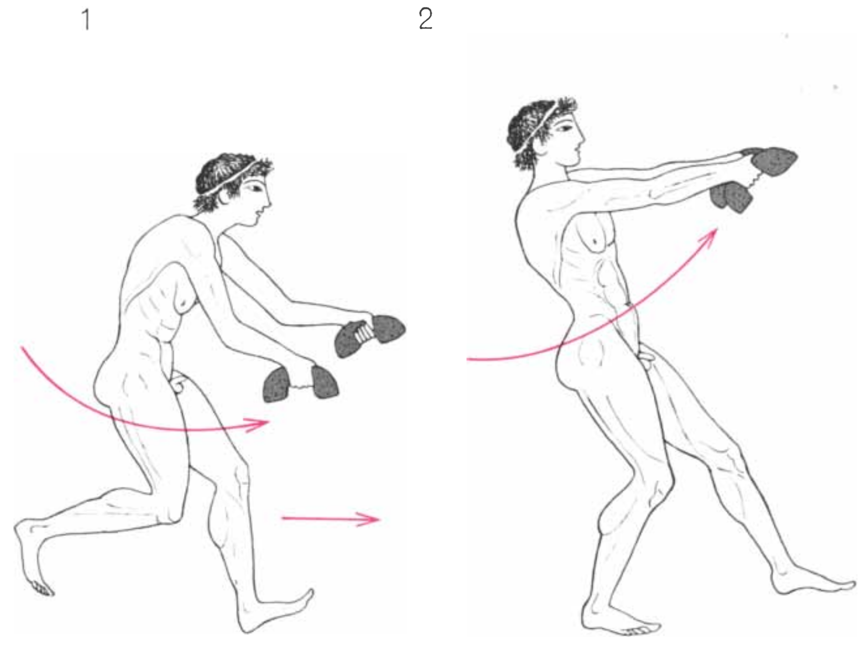
Homer describes the fight between Epeius and Euryalus as follows: "Having adjusted their belts, the two boxers go to the center of the arena. Face to face, they raise their mighty fists; they throw themselves at each other; they engage their powerful hands. Their jaws grind horribly; the sweat pours down their limbs. Epeius hurls himself on his opponent, who casts a lost look about him as Epeius punches him in the jaw. Just as a fish sometimes is thrown on the shore by a gusty north wind and then is swamped by a black wave that covers him with seaweed, so Euryalus is cast head over heels on the ground. The chivalrous Epeius picks him up and sets him on his feet again. His friends flock around him and conduct him across the ring with his legs dragging, his head lolling and his mouth spitting clots of blood. It is an unconscious man that they carry away, taking along the two-handled mug they have picked up for Euryalus."

Homer next recounts a wrestling match between the two illustrious warriors Ajax and Ulysses. Wrestling was perhaps the most popular sport in ancient Greece; it was the chief feature of the athletic training in the palaestras, gave rise to many metaphors in Greek literature and was the most famous accomplishment of muscular heroes such as Hercules and Theseus. Less brutally conducted than boxing, the wrestling competition was a contest of strength, balance, swiftness, skill and judgment. The object was simply to throw the adversary to the ground; the wrestling stopped as soon as one contestant or the other was knocked off his feet. Victory went to the man who felled his opponent three times. The match between Ajax and Ulysses goes on for a long time without either man being thrown, and Achilles finally ends it and calls it a draw.

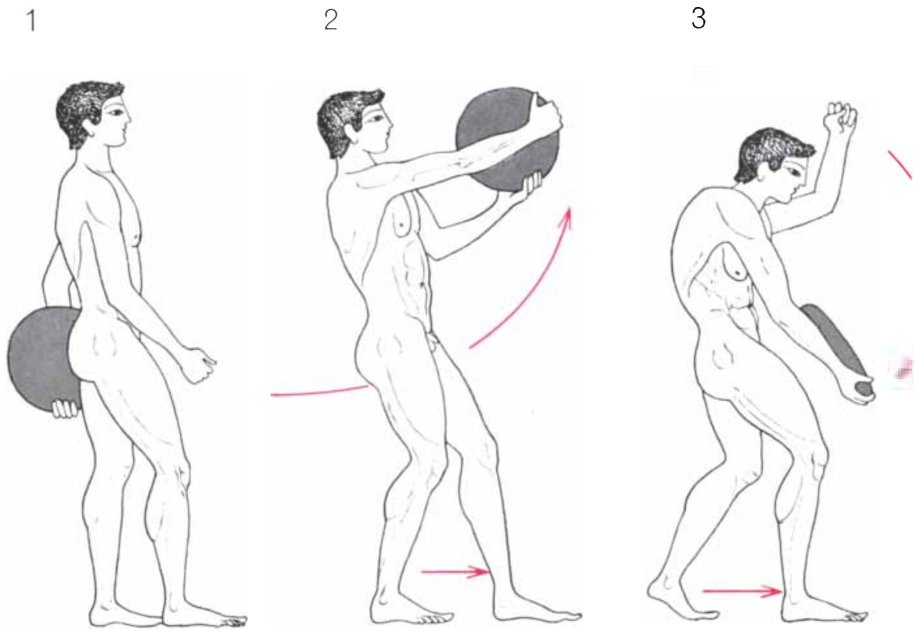
There follows an account of another event that featured Achilles' games: a footrace between Ulysses, Ajax and Antilochus. They run from a point near Patroclus' funeral pyre to a post some distance away and back. Antilochus is no match for his illustrious opponents, and the race develops into a nip and tuck contest between Ajax and Ulysses. As in the chariot race, the gods again intervene. Ajax is leading, with Ulysses so close on his heels that "his feet hit the tracks left by Ajax before the dust can cover them," when Ulysses calls on his protectress, the goddess Athena: "Hear me, goddess, and help me in your mercy. Lend wings to my feet." Athena not only accelerates Ulysses' limbs; as they near the finish line she causes Ajax to stumble so that he falls face-down into dung left by the cattle Achilles had slaughtered at the funeral pyre. Ulysses is the winner and receives a silver bowl.

In later times the Greeks built a special type of structure for footraces known as the stadium, from a Greek word (*stadion*) that is actually a measure of length. The stadium took the form of an elongated parallelogram of a certain length, usually about 180 meters, or 600 feet. The best-preserved of the ancient stadia today is one located on a stony ledge above the temple at Delphi. Footraces were based on the stadium length: sprinters ran a single length (about 200 yards) or a full lap to the end and back (400 yards); distance races, called *dolichos,* covered seven, 12, 20 or 24 stadia.

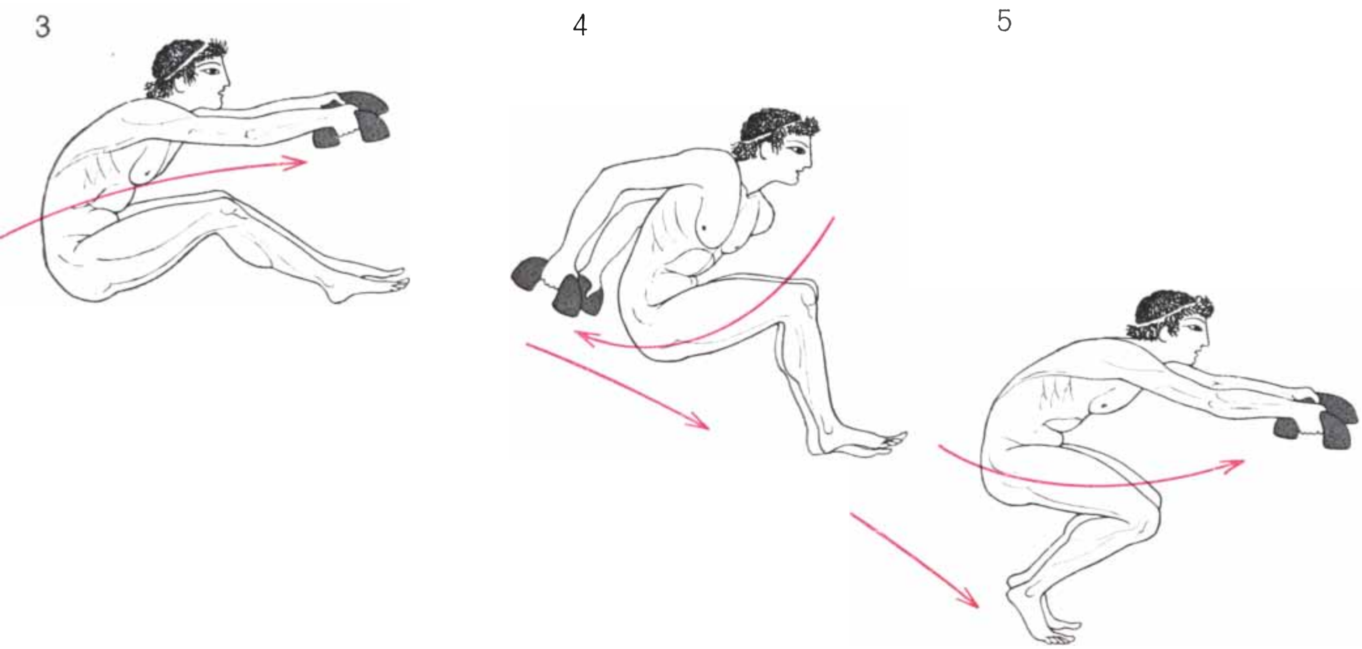
Unfortunately, as I have mentioned, we cannot compare the performances of the Greek runners with those of modern times, because the Greeks lacked a means of timing races. We do, however, have pictures of the runners, painted on vases and other objects, that show their running styles. These depict the violent exertions of the sprinters and the long, relaxed strides of the distance runners. From these pictures it might well be pos-



LONG JUMP was executed from a standing or a running start. This sequence, based on research by the English scholar E. N. Gardiner, shows the running long jump with weights.



DISCUS THROW was traced by Gardiner through these steps. The discus first is lifted high (*1, 2*) and then is lowered, resting on the right forearm, as the left foot is drawn back or

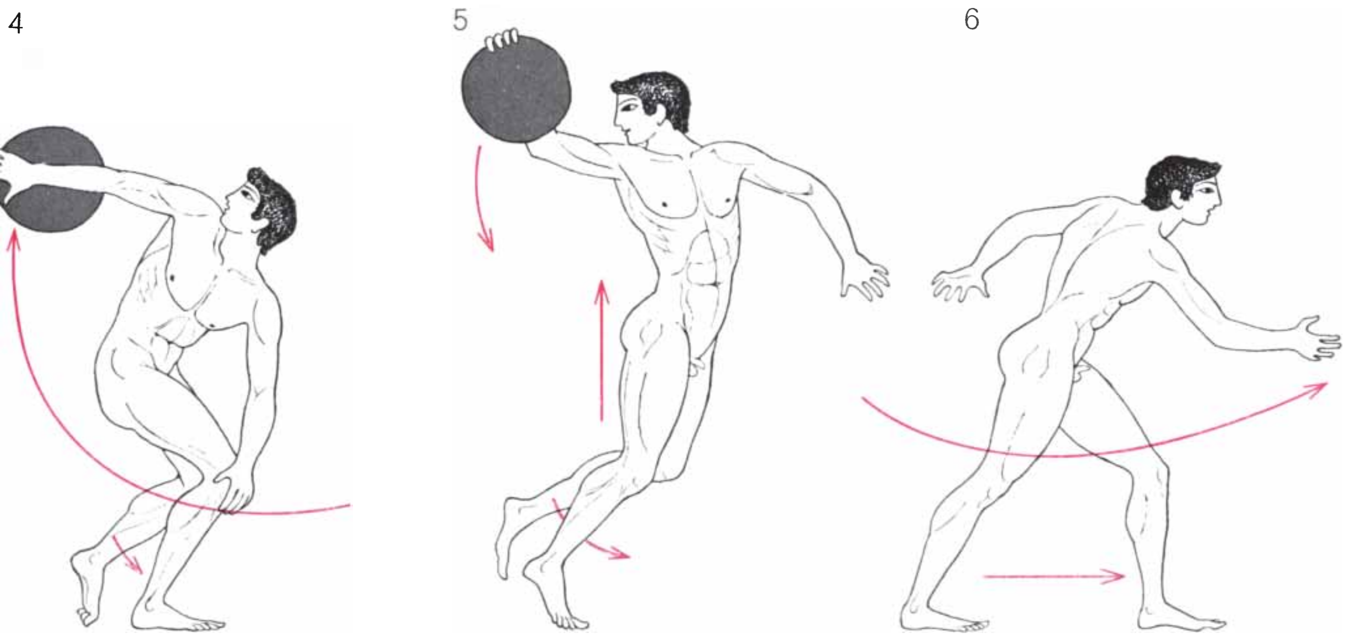


The contestant approaches the mark (*1*) and takes off with a forward swing of the weights (*2*). Once past the peak of the jump (*3*) he thrusts the weights backward to give himself a final push (*4*), and on landing he uses the weights to keep from falling back (*5*).

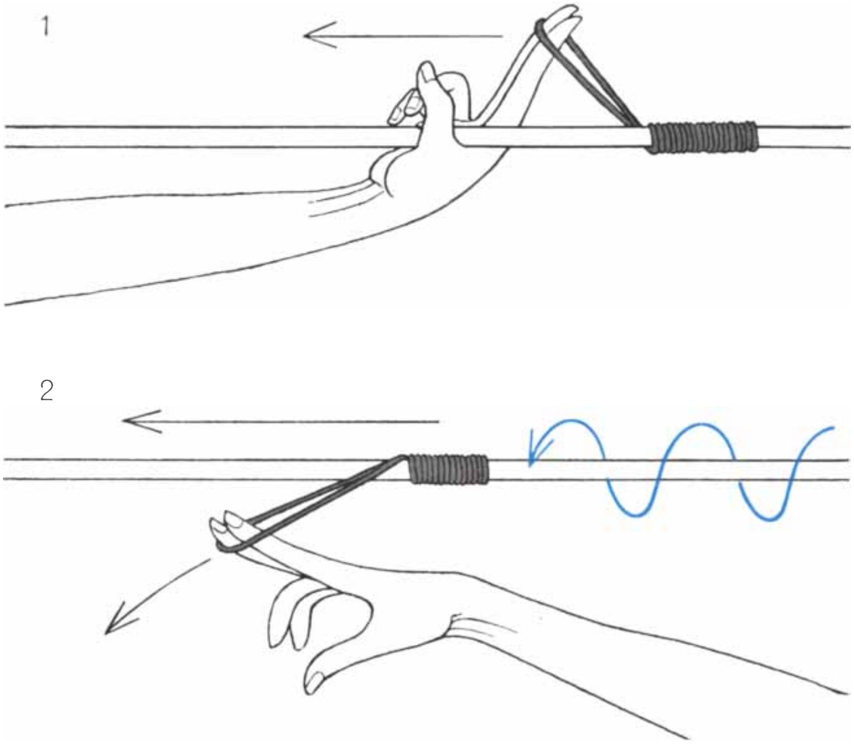
sible to produce today motion pictures of the runners in action. Miss Germaine Prudhommeau, a historian of the dance, has succeeded in reproducing the steps of some ancient Greek dances by making a filmstrip of pictures on vases of different stages of the dance, and I believe the same kind of reconstruction is possible for footracing.

The games organized by Achilles at Troy ended with jousts between some of the celebrated Greek warriors. One of these engaged Ajax and Diomedes, armed with lances and shields. The victor would be he who first succeeded in wounding his opponent. Diomedes repeatedly thrust at Ajax' neck with his lance, and Ajax pierced Diomedes' shield, although without inflicting a wound. Alarmed by the rising heat of the attacks, the onlookers made the two heroes stop the contest before either was hurt. Combats of this kind were eventually abandoned; they do not appear among the events in the later Panhellenic games. Still later, however, similar individual combats were the special delight of the crowds that crammed the amphitheaters of Rome.

The Panhellenic games, bringing together athletes and spectators from the various independent cities of ancient



the right foot advanced (*3*). The thrower moves through the position of the well-known statue of the *Discobolos* (*4*) to reach the peak of his windup (*5*). The launching movement, an underhand swing (*6*), ends with a twisting motion of the body to the left.



JAVELIN was hurled with the aid of a leather thong wound around the shaft. The thrower passed one or two fingers through a loop in the thong (*1*) and hurled the javelin with a snapping motion (*2*) that made it rotate, increasing the speed and accuracy of its flight.

Greece, were staged at the sites of the principal temples: Delphi, the Isthmus of Corinth, Nemea in Argolis and particularly at Olympia on the shores of the Alpheus River near the western coast of the Greek peninsula. The games were held in honor of Zeus and Hera, the chief gods on Mount Olympus, and they were always opened and closed with religious ceremonies. Concerts, readings by poets and orations formed part of the celebration, but the main events were athletic. For the Greeks, who were not a single nation but a loose fraternity of rival cities united only by a common language and religious traditions, the games served as an instrument of pacification and friendly communication. Their advent was announced by sacred heralds carrying the message from city to city, whereupon any hostilities would promptly be suspended and people from all over the Greek world would flock to the site of the games. Any person, free, slave or barbarian, could attend as a spectator—with the curious exception of married women.

The participating athletes, freeborn Greeks, went into intensive training for a month beforehand. Participation was not limited to adults; there were many special events for children. For the adult athletes there was a standard schedule of events: chariot and horseback races in a hippodrome and contests in the stadium that included footraces at various distances, boxing, wrestling, a catch-as-catch-can combat called the pancratium and the pentathlon, which consisted of a footrace, a long jump, wrestling and hurling the discus and the javelin. Curiously, although the Greeks were at home in the water as a seafaring people, there were no Olympic contests in swimming or boat racing.

The discus and the javelin were so popular as features of the games, and are so thoroughly illustrated in Greek art, that they are still recognized as symbols of the ancient games. The discus, usually somewhat heavier than the one used today (which weighs two kilograms, or almost four and a half pounds), was tossed from behind a line (not from a circle) in a style rather different from the present one. Instead of making a complete rotation of the body before releasing the disk, the Greek discus-thrower raised it above his head with both hands, bent swiftly toward the right with the discus in his right hand and then turned forward again to hurl it, depending on the power of the semirotation of the trunk for the force of the throw. As a result the discus-throwers developed a pad' of abdominal muscles above the waist that is characteristic of the statues of athletes of ancient times but is not often seen even in weight-throwers today.

Javelin-throwing was a test not so much of strength as of skill and accuracy. The object was not to throw the javelin farther than the other contestants but to hit a distant mark on the ground. The javelin, about as long as a man's height and as slender as a finger, was very light. A leather thong about a foot to a foot and a half long was wound around the shaft, and the thrower, passing his fingers through a loop at the end of the thong, hurled the javelin so that it rotated in flight. This served to give the throw both accuracy and distance. What a javelin-hurler needed most was long, powerful fingers. (Achilles, by the way, did not include the javelin throw in his games at Troy, in spite of the great popularity of that sport. He omitted it to deny glory to his rival Agamemnon, who was known to be a redoubtable javelin-thrower.)

The only jumping event in the ancient Olympics was the long jump of the pentathlon. The manner in which it was performed is not absolutely clear, although we do know that the jumper usually held in each hand a kind of dumbbell made of stone or bronze and weighing anywhere from two to 11 pounds. The weights were thrust forward and then back to add distance to the jump, which was apparently made either with or without a running start. One puzzling fact is that contestants are reported to have covered 50 feet or more; it is possible that the event, in such cases, consisted of a sequence of five jumps from a standing start.

The pancratium of the Greek Olympics was a combination of boxing and wrestling that contained brutal aspects of both exercises. Any kind of blow with the fists or the feet was permissible, and every part of the adversary's body was a legitimate target. The only maneuver that was barred was poking one's fingers into the eyes or orifices of the opponent's face. The combat began with the contestants standing, continued on the ground and ended only when one of the combatants was reduced to helpless surrender. Needless to say, since there were no weight restrictions, a lightweight had no chance to win in this sport.

The Olympic games began, as I have mentioned, in 776 B.C. and were held at four-year intervals until A.D. 393—a period of nearly 12 centuries. During the era of Greece's glory they were characterized by pure amateurism and immeasurable rewards of honor. The winner of each event received a crown of olive leaves from a sacred tree that according to tradition had been brought to Olympia by Hercules from the country of the Hyperboreans. His homecoming was triumphant; in at least one case, we are told, the athlete entered through a breach in the city walls that the citizens had leveled so that he could be welcomed at an entrance not previously trodden by human feet. At Olympia a winner could have a statue of himself erected in the sacred grove where the temples stood. If he could afford the expense, he might also ask a poet to compose an ode in his honor. Foremost among these odists was Pindar, whose eulogies of athletes were famous for their lyricism. One of them runs:

"When an athlete gives himself with his whole heart to the noblest ambition, he does not count the expense or the effort. We must offer those who have attained this end our unstinted homage, and it must come from a heart without envy. For their various labors all men—shepherds, laborers, hunters, fishermen—like to receive wages; everyone is driven to work to avoid the pangs of hunger. But he who achieves distinction in games or in war finds his highest reward in praise from the lips of his fellow-citizens and even strangers."

The tradition and spirit of the Greek Olympic games carried over to the Etruscan culture in the Italian peninsula and to the beginning of the Roman era. As the glory of classical Greece faded, however, so did the brilliance of the quadrennial games. In Rome they became mere circuses and were dropped altogather after A.D. 393, not to be revived for nearly 1,500 years. Renewal of the games came in 1896, when the first modern Olympic meet was held in Athens through the efforts of the French educator Baron Pierre de Coubertin. The modern Olympic games have of course gone far beyond the ancient meets in the magnitude and the diversity of their events, covering nearly the entire range of modern sports.

Fortunately the 20th-century Olympics have also maintained thus far the original Greek ideal of amateurism, as expressed in 1894 by Baron de Coubertin: "Before all things it is necessary that we should preserve in sport those characteristics of nobility and chivalry that have distinguished it in the past, so that it may continue to play the same part in the education of the peoples of today as it played so admirably in the days of ancient Greece."

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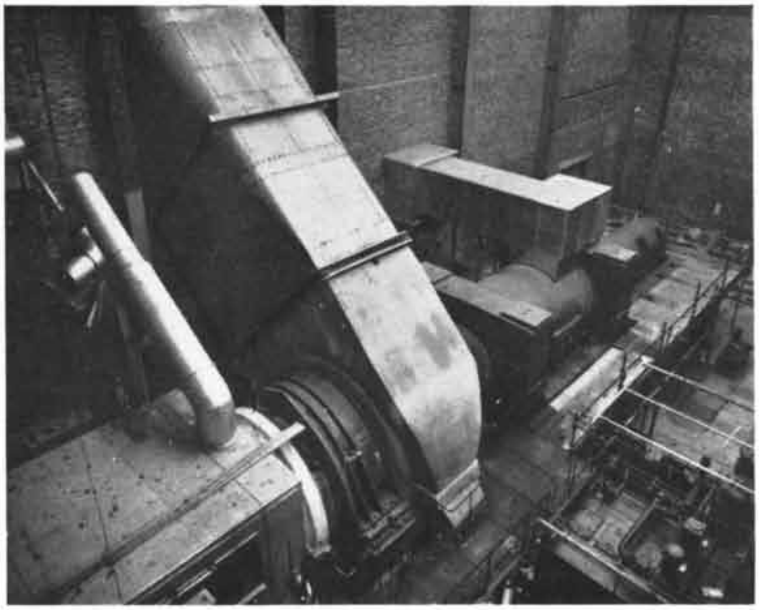

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MOVEMENTS OF THE EYE

In which a special camera records where people look in the course of such activities as driving and looking at pictures. It appears that the eye fixes on many things of which the viewer is not aware

by E. Llewellyn Thomas

To look closely at something is to turn one's eyes so that the image falls on the fovea, a specialized area smaller than the head of a pin that lies near the center of the retina. Only in this tiny region are the receptor cells concentrated with sufficient density to provide detailed vision. As a result not more than a thousandth of the entire visual field can be seen in "hard focus" at a given moment. Yet the human eye is capable of discerning in considerable detail a scene as complex and swiftly changing as the one confronting a person driving an automobile in traffic. This formidable visual task can be accomplished only because the eyes are able to flick rapidly about the scene, with the two foveae receiving detailed images first from one part of the scene and then from another.

Therefore most of the time our eyes are jumping from point to point. These movements and fixations can be recorded in various ways. One method is to photograph the bright spot you can see when a light shines on the eye. This bright spot is the reflection from the convex surface of the cornea. Because the radius of curvature of the cornea is smaller than the radius of the spherical eyeball, the angle of reflection changes when the eyeball rotates and the bright spot appears to move. These movements can be correlated with the movements of the eye's line of sight.

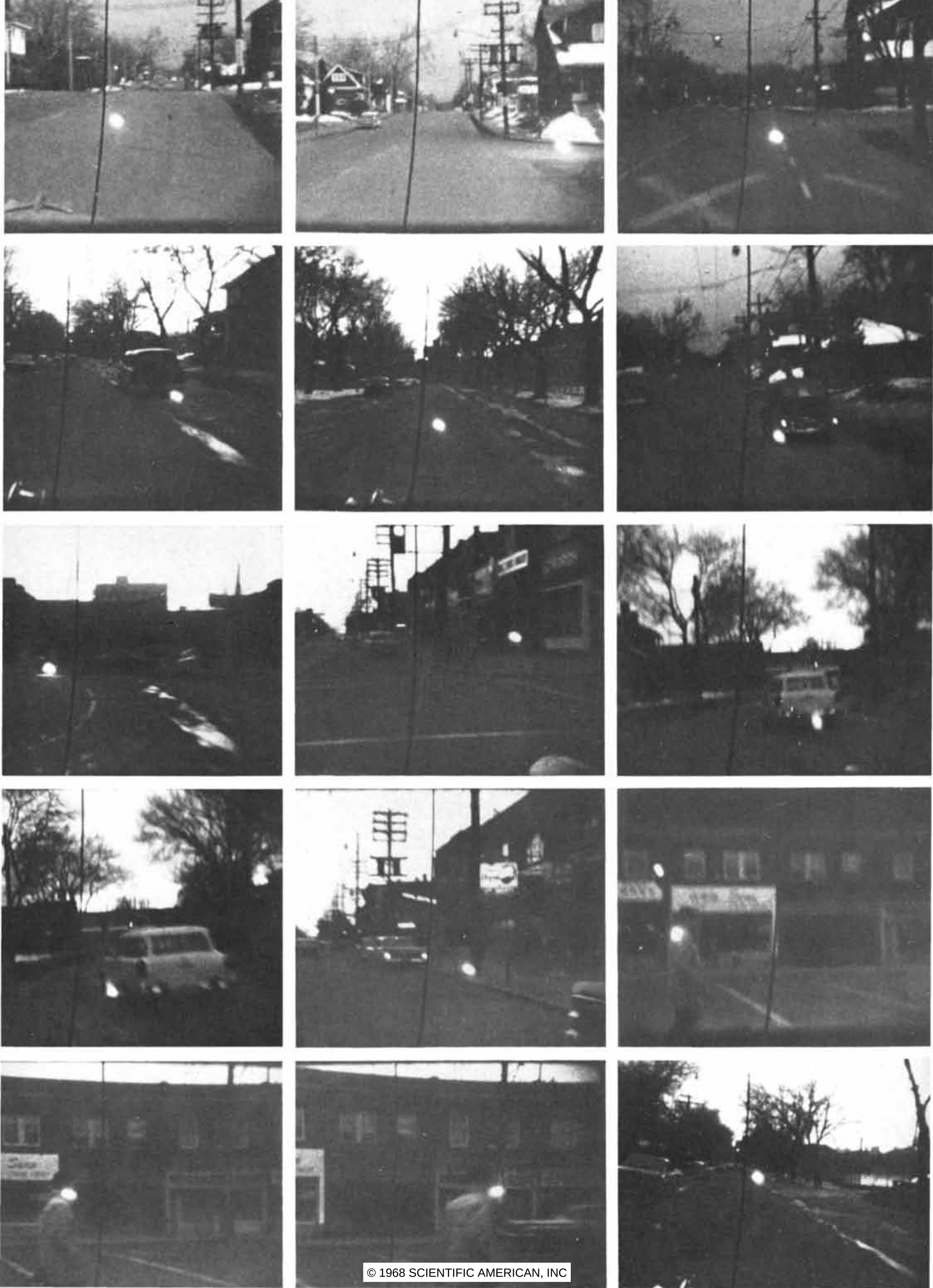
When such a photographic record is combined with a motion picture of the scene ahead of the viewer, it reveals the features that attracted his notice, held it or were overlooked. Such records have useful applications, for example in the design of highway signs and radar displays. They can show how critical details in an X-ray plate or an aerial photograph are sometimes overlooked, even when the viewer thinks he has scanned the picture carefully. In our laboratory at the University of Toronto we have been using developments of this method to study how the human eye attacks such visual problems. We have also been interested in how the patterns of eye movement are affected by psychological disturbances and drugs, and how a sequence of eye movements and fixations can be related to the processing of information in the brain.

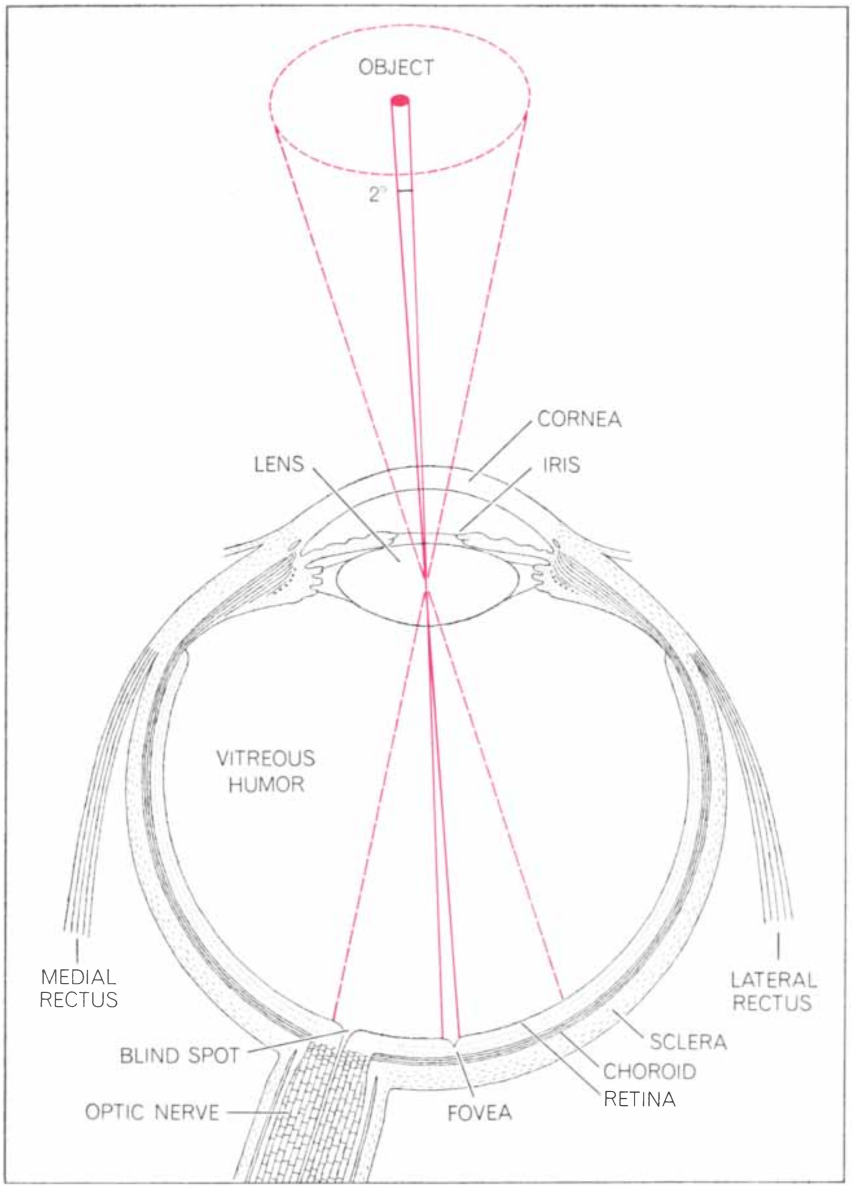
The most common major eye movement is the saccade: the rapid jump the eye makes as it moves from fixating one part of a scene to fixating another. The fixations themselves usually last less than half a second, but their duration depends on the character of the scene and what the viewer is doing. The jump between fixations takes only a few milliseconds. Vision is greatly reduced not only while the eye is actually moving during the saccade but also for a short period before it starts to move. One can appreciate this reduced vision if one tries to observe one's own eye movements in a mirror.

The speed of the saccade depends on the saccade's length and direction, and the speed also differs from individual to individual. The flick may be so rapid that the eye's angular velocity may reach more than 500 degrees per second. This velocity is not under conscious control; an effort to slow it will only break the saccade into a series of shorter movements. If at the end of the saccade the fovea is not "on target," the eye adjusts by making one or more small corrective jumps. The path the eyes follow between two fixation points may be straight, curved or even hooked, but once the eye is launched on a saccade it cannot change its target. It is as if the points in the visual field were recorded as a set of coordinates in the brain. The difference between the coordinates of a fixation point at one instant and the coordinates of the next fixation point constitutes an "error" signal to the eye-movement control centers, and the resulting movement of the eye is directed in a manner analogous to what an engineer would call a simple position servomechanism.

The eye moves so frequently and rapidly that the pattern it weaves can be recorded only by instruments. Methods of recording eye movements include contact lenses, suction cups and photoelectric devices. When the head must be left as unencumbered as possible (as in recording the eye movements of astronauts during flight or in recording eye movements under closed lids), the method of choice is the electro-oculograph. Early investigations of eye movements in reading (by Raymond Dodge) and in the ex-

VIEW THROUGH WINDSHIELD, shown in the sequence of photographs on the opposite page, indicates (*white spot*) where the viewer inside the automobile was looking as it moved along the street. The photographs were made with a device that records both the scene before a viewer's eyes and a spot of light reflected from one of his eyes. This device is worn on the head of the viewer, as shown on page 91. A vertical line in the optical system of the device appears at the center of each photograph. It indicates, by its position with respect to the scene, when the observer's head has moved. Reading from left to right and top to bottom, the features of the scene that drew the eye were (*1*) the street pavement, (*2*) a pile of snow, (*3*) the broken line painted on the pavement, (*4*) a parked automobile, (*5*) the street pavement, (*6*) a moving automobile, (*7*) a patch of snow in the street, (*8*) a storefront, (*9 and 10*) an automobile as it is overtaken, (*11*) the base of a telephone pole, (*12, 13 and 14*) the shoulder and face of a pedestrian as he crosses the street and (*15*) the roadside ahead.





DISTINCT VISION is limited by the size of the fovea, a region of the retina where the receptor cells are tightly packed together. Whereas the retina as a whole covers a visual angle of approximately 240 degrees, the fovea subtends an angle of only about two degrees. Consequently, to perceive the details of a scene the two foveae of the eyes must be moved.

amination of pictorial material (by A. E. Brandt and Guy T. Buswell) were made by photographing with a stationary camera the moving corneal reflection of a viewer whose head was firmly fixed. Then the record had to be rather laboriously related to the scene being viewed.

The problem of continuously relating the eye to a changing scene was solved by Norman H. Mackworth and Jane F. Mackworth. The system they developed (at the Applied Psychology Research Unit in Cambridge, England) employed one television camera to record a magnified image of the corneal reflection and a second television camera to record the scene in front of the viewer. On the television monitor the combined output of the two cameras showed the scene with the bright spot of the corneal reflection moving over it.

The next step was to allow the viewer to move his head and body so that it would be possible to study the many situations in which the scene is constantly changing and the viewer is moving his head and body as well as his eyes. To accomplish this Norman Mackworth and I, working at the Defence Research Medical Laboratories in Toronto, contrived an optical system mounted on a helmet; this system enabled us to record a composite motion picture showing the changing scene in front of the wearer together with where he was fixating within the scene and his head and body movements. At various times we used fiber optics to transfer the combined image to a 16-millimeter motion-picture camera or mounted a small television camera on the helmet. The most convenient apparatus for studies outside the laboratory, however, was a "homemade" eight-millimeter camera weighing only a few ounces that we mounted on the helmet behind the optical system. The overall accuracy of this system is two degrees of solid angle, which is about the same as the area of acute vision subtended by the fovea (the size of a dime held at arm's length).

Such a system obviously has its limitations. The viewer has to wear equipment weighing several pounds on his head. His vision in one eye is reduced by the half-silvered mirror that picks up the corneal reflection [*see illustration on cover*]. There is the possibility of the helmet's moving on the viewer's head during the experiment and upsetting the calibration. There is also the problem of the convergence of the eyes when one is viewing close objects, and of parallax errors. The useful field of the recording is limited to about 30 degrees in the horizontal. Nonetheless, for the study of real-life situations in which head and body movements usually play an important part, and in which the scene is continuously changing, some device such as the Mackworth camera is necessary.

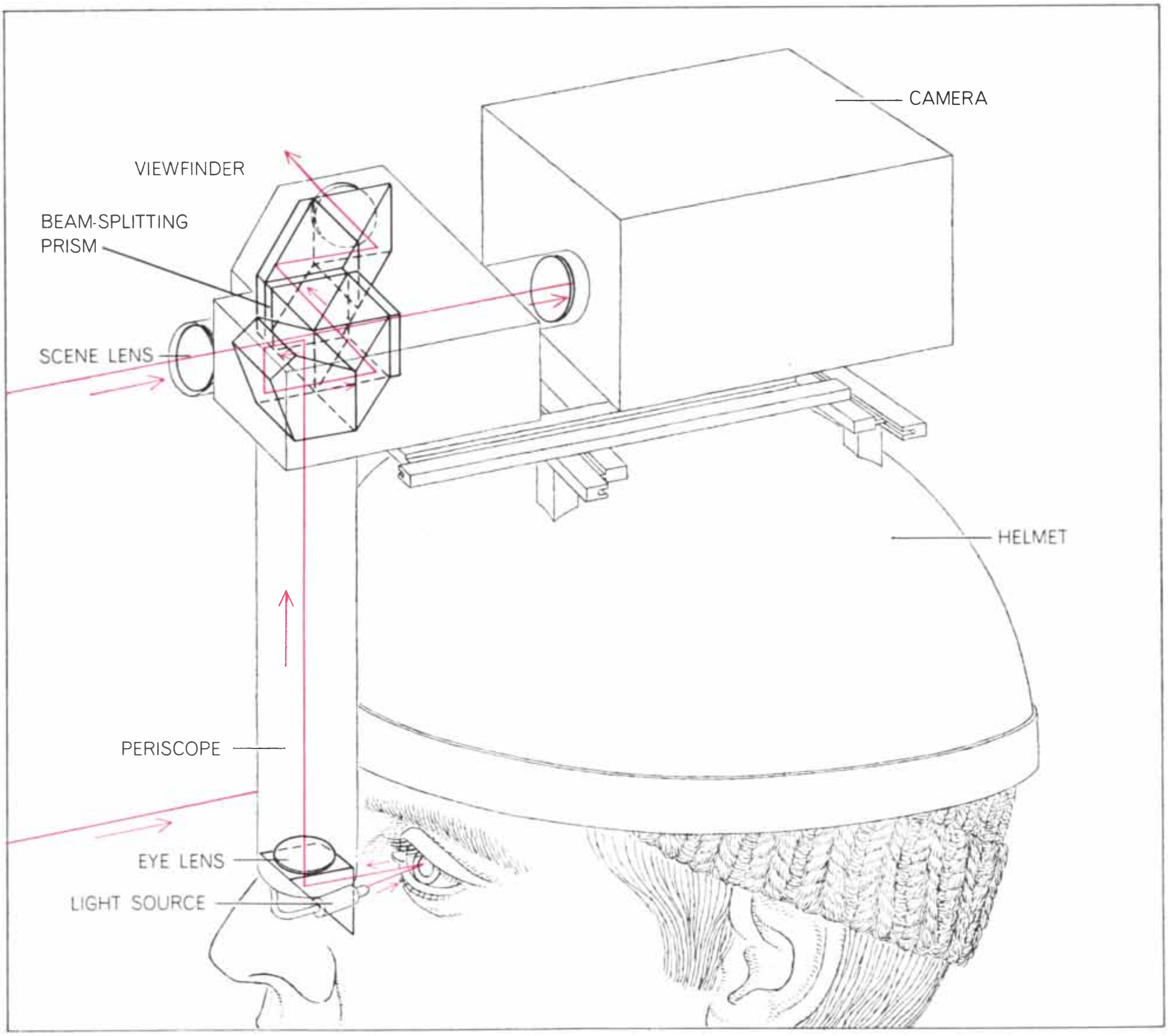
Mervyn Thomas, Jane Mackworth and I used the camera to obtain some very interesting motion pictures of the eye movements of drivers in actual traffic. We saw how the driver's eyes dart about in their search for information. When an automobile is moving, the driver's eyes are constantly sampling the road ahead. At intervals he flicks quickly to the near curb, as if to monitor his position, but for such monitoring he seems to rely chiefly on the streaming effect—the flow of blurred images past the edges of his field of vision. The edges of other vehicles and sudden gaps between them attract visual attention, as do signs along the roadside and large words printed on trucks. If something difficult to identify is encountered, the fixations are longer and the eyes jump back to view it again.

The faster the automobile is moving or the heavier the traffic, the more frequent are the saccades. When the driver stops at a traffic signal, his eyes seem to move less often and rather aimlessly, but they jump toward anything novel that appears. On a main highway the cars passing in the opposite direction attract quick glances. A broken white line along the center of the road sometimes gives rise to vertical flicking movements. The eyes are also drawn to objects on the skyline such as tall buildings.

One of the strongest visual attractions seems to be flashing lights, such as those of a turn indicator on a vehicle ahead or of a neon sign at the side of the road. This demonstrates an important characteristic of human vision. When the image of an object strikes the periphery of the retina, the eyes swing involuntarily so that the object is focused on the two foveas and can be perceived in detail. Although the periphery of the retina is poorly equipped for resolving detail, it is very sensitive to movement seen in the "corner of the eye." A flashing light therefore serves as a powerful visual stimulus. On several occasions during our experiments a driver continued to glance in the direction of the flashing indicators of a car ahead, even after it had made its turn (a phenomenon Norman Mackworth had observed earlier in simulated driving studies with the television eye-marker).

I noticed another example of peripheral attraction when we recorded the eye movements of a pilot landing a small aircraft. At touchdown the pilot usually maintained his sense of direction by the streaming effect while looking rather aimlessly ahead up the runway. I believe this aimless looking reflects a readiness to react visually to the unexpected. On one occasion the pilot's eyes flicked away to fixate repeatedly on an object at the side of the runway in a flurry of rapid saccades. His eyes continued to be drawn over even after he must have identified the object as one of the spruce seedlings used on that airfield as snow markers, which our record showed he was fixating accurately.

This sensitivity to a moving or novel object at the edge of the scene demonstrates that the retina functions as an effective wide-angle early-warning system, and that a strong peripheral signal will continue to pull the eyes. This, I suppose, is the objective of the designer of flashing neon signs. If so, it would seem



EYE-MARKER CAMERA tracks and records the eye's glance. The image of a spot of light, reflected from the cornea, is transmitted by an optical system in the periscope through a series of prisms. This serves to superpose the eye-marker image on the scene image. The combined image can be monitored through the viewfinder as it is photographed by the motion-picture camera.

better for him to exercise his skill elsewhere than along the sides of a highway.

Certain hazards in the operation of an airplane have been reduced by studying the visual behavior of the pilot. It is obviously desirable that the instruments in the cockpit be located so that the most important ones come most easily to the pilot's eyes, in the same way that the important controls come most readily to his hands. During the time it takes to make a single fixation an aircraft will have traveled several hundred yards. Nevertheless, in the past engineering considerations often took precedence over human ones. By making motion pictures of the pilot's eye and head movements during flight, Paul M. Fitts, J. L. Milton and R. E. Jones (in a study for the U.S. Air Force in 1951) identified the instruments that were used more often and the pattern in which they were viewed in various phases of flight. From this study and similar investigations in human-factors engineering, standardized layouts for instruments and controls were drawn up. Their wide adoption has helped to reduce what were two of the leading causes of aircraft accidents: misreading instruments and operating the wrong control.

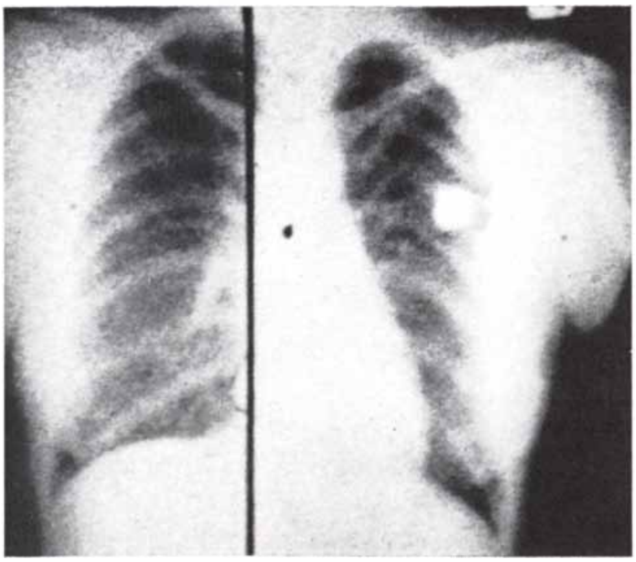
In reading, as in driving an automobile, the predominant eye movement is the saccade, but the saccade of reading is initiated in a different way. When one gazes at a line on a printed page, only three or four words can be seen distinctly. If every word in the line is to be read, the eyes must jump two or three times. How often they jump depends not only on the reader's ability to process the visual information but also on his interest in what he is reading. Thus the reading saccade is initiated not so much by the image on the periphery of the retina as by a decision made within the central nervous system. Fixation times lengthen as the material becomes harder to comprehend. The eyes may return at intervals to words scanned earlier; these regressions indicate the time it has taken the reader to recognize that his processing of the information was incomplete or faulty. Because we have long experience with the English language we anticipate common sequences of words and so may fixate only the first few words of a phrase.

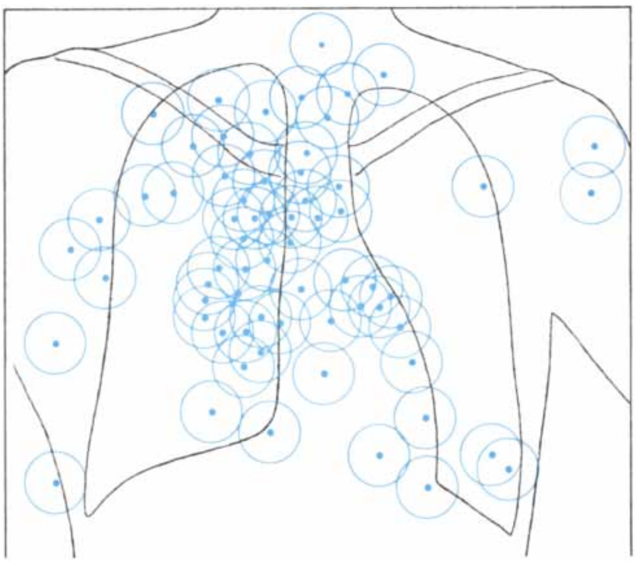
When people of Occidental cultures read, they habitually move their eyes from left to right and top to bottom, and so they usually look first at the upper left-hand part of a page. This may not apply, however, if the format of the page is broken up, as it is in a newspaper. When someone is looking at pictures or groups of pictures, the scanning patterns seem to be individualistic. They are also consistent, but there is no preferred sequence in which areas are inspected. As Mackworth has remarked, the order of visual fixations seems to matter no more than the sequence in which a series of shots is taken for an amateur motion picture: "Shoot now and think later."

Harley Parker and I recorded and compared the visual behavior of an artist and a nonartist as they examined a series of paintings. The pitfalls in reporting such subjective studies are obvious, but there seems no doubt that many painters are highly successful in directing the movements of our eyes. The artist viewer appeared more sensitive to this, particularly with respect to more abstract pictures. The eyes of both men, however, were drawn to discontinuities, including the edges of the picture itself.

This agrees with recent neurophysiological findings that contours and borders, such as those in a checkerboard, are strong stimuli of the evoked voltages that can be measured in the brain when such items are presented to the eye. This might also be expected from the fact that the border defines the shape and is a key information element in a scene. The visual pull of such borders may constitute an impediment if the viewer is searching for a low-contrast feature, such as an abnormality in an X-ray film of the chest. Edward L. Lansdown and I recorded the eye movements of a group of student radiologists as they inspected a selection of chest X rays. Our records showed that the students had carefully examined the edges of the heart and the margins of the lung fields, and indeed these are important regions for signs of disease. But large areas of the lung fields were never inspected by most of the students in the group, even though they thought they had scanned the films adequately.

To be sure, the students who had made the most complete visual examinations were the ones with the most experience in X-ray interpretation. Nevertheless, William J. Tuddenham of the University of Pennsylvania School of Medicine and L. Henry Garland of the





X-RAY SEARCH, made by student radiologists looking for signs of pathology, was studied by means of the eye-marker camera. Appearing on an X-ray plate of the chest (*left*) is the mark of a single eye fixation (*white spot*) made by one of the students. A drawing of the lung area (*right*) displays a summary of the eye fixations of a student who was engaged in the rapid examination of a single X ray. The area of sharp vision is indicated (*circle*) around each fixation point. Large areas of the lung fields were not explored.

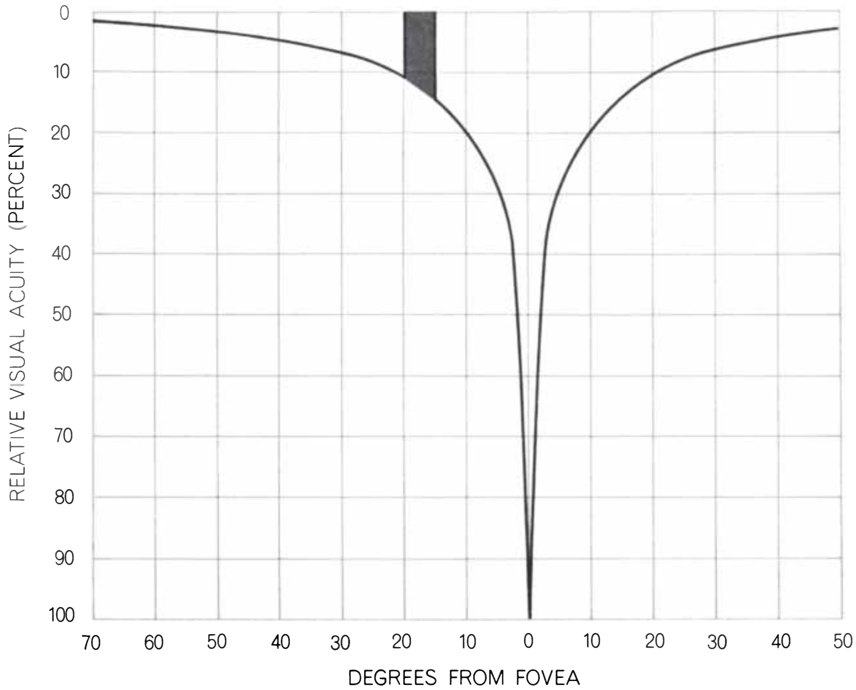
Stanford University School of Medicine tested groups of trained radiologists and found that they missed 25 to 30 percent of "positive" chest X rays under conditions in which their errors must have been largely due to failures of perception. Joseph Zeidner and Robert Sadacca of the Human Factors Research Branch of the U.S. Army have reported similar failures in the interpretation of aerial photographs by a group of skilled military photointerpreters: the interpreters neglected to report 54 percent of the significant signs. It appears that the structure of the image under examination may obliterate the pattern of scanning an observer intends to follow; his gaze is drawn away, so that he literally overlooks areas he believes he has scanned. Moreover, low-resolution peripheral vision often determines where the viewer does not look. Here the potentiality for errors is obvious, particularly in a task performed under pressure.

In this connection there are some interesting differences between the way children and adults look at pictures. Norman Mackworth and Jerome S. Bruner, working at the Center for Cognitive Studies at Harvard University, have found that children show more short eye movements and concentrate on less informative details. They are less consistent in their viewing patterns, and sometimes they visually trace out simple contours that adults process by peripheral vision. All of this suggests that children concentrate visually on detail more than had previously been thought.

The link between the image and the mind is a difficult one to investigate because the brain does not receive information passively but partly controls what reaches it from the eyes. Our gaze is averted from something that is distasteful; alternatively, something that has been perceived only too well may be barred from fully conscious awareness. Studies undertaken at the University of Pennsylvania by Lester Luborsky, Barton J. Blinder and Norman Mackworth have shown that people may tend to avoid accepting and remembering visual information that is associated with heightened emotion (as measured by an increase in the well-known galvanic skin response). They may deny that they ever looked at some emotionally charged feature, even when their eye-movement record shows that they had.

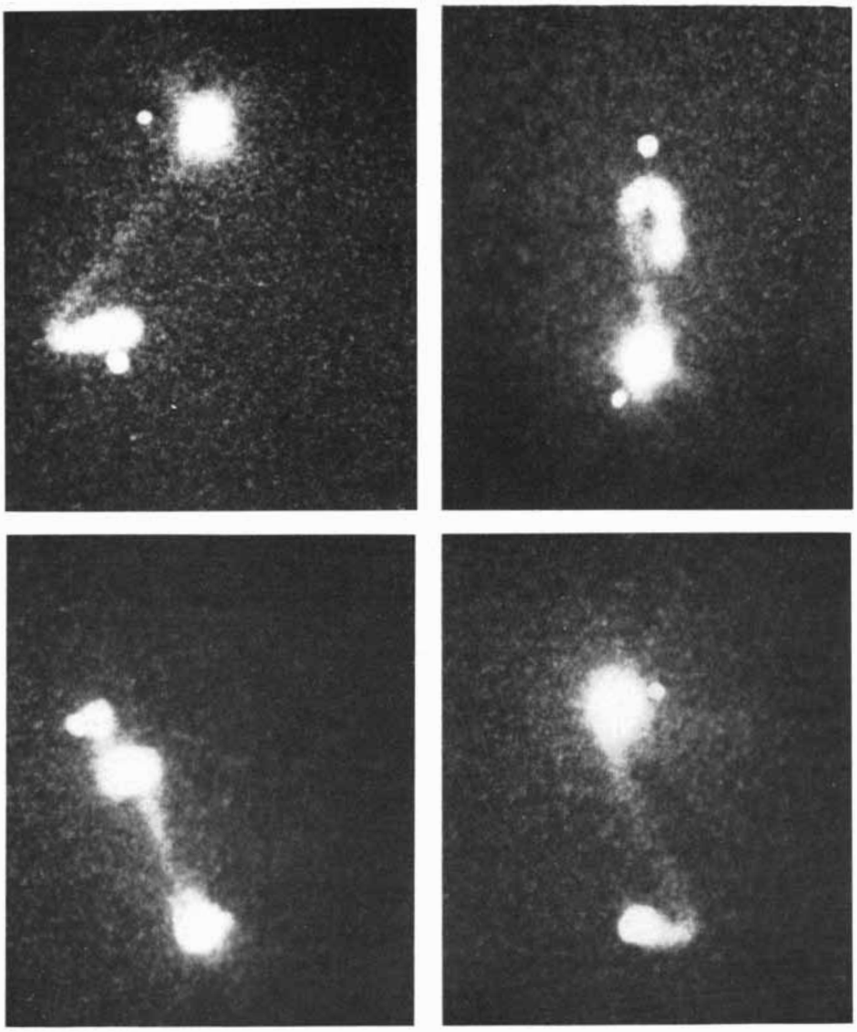
This rejection of visual information may reach pathological levels, the most extreme example being hysterical blindness. Eugene Stasiak and I explored the visual reactions of a group of patients at the Lakeshore Psychiatric Hospital in Toronto. We recorded the patients' eye movements while they were looking at life-size photographs of themselves and other people. We found that the scanning patterns of the patients differed significantly from those of people in a nonpatient control group. Whereas the people in the control group (whether they were looking at pictures of themselves or at pictures of others) paid most attention to the face, the psychiatric patients avoided looking at the face. The duration of the patients' fixations on the photographs also differed, at times being markedly shorter than the average time of the control group and on occasion distinctly longer. We believe both the different fixation times and the avoidance of the face reflect a tendency on the patients' part to reduce their intake of information. This tendency may arise from distortions of perception or from differences in interpretation. With several patients there appeared to be a relation between psychiatric history and viewing pattern; for example, the patient's eyes might return again and again to a part of the body significant in his own psychiatric history.

In other experiments Hyam Day and I investigated the intake of visual information by subjects who were not suffering from a psychological disturbance but



VISUAL ACUITY is greatest in the foveal region of the retina. At the point where the optic nerve passes through the inner coat of the eyeball (*gray area*) there is no vision.

FIXATIONS ON INKBLOT were shown by eye-marker camera to fall chiefly on the blot's margin. The border of a form presents a high contrast and a strong visual stimulus to certain of the retinal cells. This may serve to draw the eye from other areas in the scene.



SACCADIC MOVEMENTS were elicited by stimulus lights (*small dots*). As the viewer's eye moved from a fixation on one stimulus light to a fixation on another, the path of the saccade, or eye flick, was photographed. The hook that appears in three of the paths suggests that one of the muscles that moves the eyeball operates later than the others. The experiment was arranged so that the path image would be displaced from the image of the stimulus lights.

who had been given the stimulant dextroamphetamine. Two abstract pictures, one more complex than the other, were simultaneously presented to the subject, once after he had been given a capsule of dextroamphetamine and on another occasion after he had been given an inert capsule. The film of the subjects' visual reactions showed that they spent more time examining the complex picture after they had been given the drug. This result suggests that the drug increases willingness to seek and accept visual information. Whether it also affects the ability to process the information is another question.

It is evident from other studies that when an observer's interest is aroused by what he sees, his eyes move more often. The eyes of a group of healthy young men moved nearly twice as frequently in examining photographs of attractive young women as they did during the inspection of inkblots. Incidentally, the curved edge of the female form attracts the male eye—a logical assumption for which it is pleasant to have experimental verification. Not only do the eyes move more often when the viewer is more interested; there are also more corrective jumps serving to bring the image of the object of interest toward the center of the fovea. There are, moreover, fewer eye blinks, the eyes are opened wider and the pupils are dilated [see "Attitude and Pupil Size," by Eckhard H. Hess; SCIENTIFIC AMERICAN, April, 1965].

In this way the eyes demonstrably reveal emotion. The direction of a glance may also reveal intention. It is not surprising, then, that when a person looks at the face of another person, he tends to look most at the eyes. When the other person starts to speak, however, visual attention shifts to the mouth; apparently everyone reads lips to some extent.

On a motion-picture screen the center of visual interest is also the face. To study the effects of observing violence, Richard H. Walters of the University of Waterloo and I showed a group of subjects a knife-fight scene from a motion picture. This appeared to increase the subjects' aggressive behavior (as measured by a test given the viewers immediately after the film was shown). To gain some idea of which elements in the film were most active in this regard, we recorded the eye movements of several subjects while they were watching it. The subjects spent the greatest part of the time following the faces of the two central characters; the knives themselves and the other actors received only an occasional glance.

Such movements of the eyes as they explore the environment are largely outside conscious control. Records of the movements can therefore provide insights into the processing of visual information by the brain. For example, Norman Mackworth has observed a phenomenon that he calls "looking without seeing." His subjects had been given the task of finding one number among a matrix of numbers. Mackworth noted that at times a subject's eyes would fixate on the number he was seeking, but even so he would continue the search. His eyes might make several fixations around the number, thereby breaking the scanning pattern, and then resume their searching movements. That there was recognition of the number at some level in the nervous system was indicated by the variation in scanning pattern. The subject was not consciously aware, however, that he had found what he was seeking.

In a later study Norman Mackworth, Ira T. Kaplan and William Metlay asked a group of people to watch two dials and report each time the reading on either dial had changed. The visual records of the group indicated that about a third of the dial changes that had not been actually reported had been fixated. In our studies of automobile drivers there was an instance that appeared to be similar: a driver looked straight at a red light and then started to drive right through it.

A great deal of the information that arrives at the brain from the retina fails to obtrude on the consciousness. In this connection it is startling to watch a film of one's own eye movements. The record shows hundreds of fixations in which items were observed of which one has not the slightest recollection. Yet the signals must have reached the brain because one took motor action and even made rather complex decisions based on the information that was received during the forgotten fixation. Parts of the brain appear to function rather like a secretary who handles routine matters without consulting her employer and apprises him of important points in incoming letters—but who at times makes mistakes.

Some insight into the brain's processing of information can be gained by examining the eye movements of a person who is engaged in solving a problem. For example, I have recorded the eye movements of two mediocre chess players who were studying an end-game problem. The visual patterns of the two players differed greatly; still, it was clear that both were in effect shifting the pieces to various positions on the board as they tried out a series of possible moves.

A more sophisticated approach to problem-solving was displayed by another subject, an engineer whose eye movements were recorded as he analyzed an electronic circuit. After he had studied the circuit, which I had drawn on a blackboard, I changed some of the components and asked him to decide how the alterations would affect the circuit's operation. In looking at the circuit before it was changed the eyes of the engineer had traced the essential pathway. In viewing the altered circuit he did not again explore the pathway but went directly to the parts that would be the most affected. At another time the same subject examined a series of differential equations in which I had made planned (and unplanned) errors. His eyes rapidly singled out the mistakes, making a series of short jumps that effectively narrowed down the area of his attention until they had centered on the critical terms.

The length of time that is spent in looking at a scene must obviously be related in some way to the amount of information about the scene that the viewer receives. Certain of our studies suggest that a lengthening fixation time may be associated with a diminishing intake of information. The subjects were shown Rorschach inkblots and were asked to write down what the blots reminded them of. At first their eyes darted over the entire area of the blot, making numerous fixations. As time went on the fixations became decidedly longer. Perhaps these fixation times reflect a process in which the viewer, having realized that the blot offers little or no genuine information, is adding or generating meaning rather than merely accepting it.

QUEUES

Waiting in line is done not only by people but also by such things as freight cars, airplanes, telephone calls and computer routines. Mathematical analysis of queues suggests ways to shorten them

by Martin A. Leibowitz

Airplanes stacked over an airport, shoppers waiting at a check-out counter in a supermarket, freight cars lined up for unloading at a railroad terminal and messages seeking a free path through a telegraph network all have one thing in common: they are members of a queue, or a line waiting for a service. The word "queue" is perhaps more familiar in Britain than in the U.S., but the phenomenon is the same everywhere. With the increasing complexity and crowding of human communities and the growing demand for services of all kinds, queues have become a commonplace and often unavoidable experience.

Queues have been under intensive investigation for several years by workers in a variety of fields, particularly mathematics and operations research. As a result it is possible to describe queues fairly comprehensively in terms of their causes, the special forms they take and the interesting way they grow and shrink. Emerging from this supply of information is a developing ability to control queues within the limits imposed by requirements of efficiency and economy. Notwithstanding these achievements, it seems likely that the most important and far-reaching work on queues will be done during the next few years.

Even the simplest situation involving a queue—for example a line of people waiting to buy tickets at a motion-picture theater—consists of three elements. The first is the queue itself, which is constantly being replenished by new members who join it and wait for their turn to receive the service that is being provided. The second element is the server, which can be active (e.g., a ticket-seller) or passive (e.g., a runway at an airport). Thirdly, the queue and the server have a physical location, which is termed the facility.

There are many variations on this basic theme. A queue can have more than one server. If it does, the situation can be the one found at highway tollbooths, where each server has his own queue, or the one found in barbershops, where each server draws from a common queue. Members of a queue can be served in the order of their arrival—the usual first-come-first-served arrangement—or at random, as sometimes happens at a taxi stand or in a crowded store. A queue can have virtually unlimited length, as the queues encountered by visitors to a world's fair often do. Alternatively the facility can impose a limit, as a small waiting room at a doctor's office does. Indeed, the facility may become so taxed that waiting is no longer allowed and new arrivals are turned away, as they frequently are at crowded parking lots.

Normally all the members of a queue are treated alike, but there may be a system of priorities giving certain members precedence over others regardless of arrival time. This is what happens in a hospital's outpatient department, where emergency cases are treated as soon as they arrive even if other patients are waiting. Priority is also given in supermarkets, where express check-out lanes are provided for customers with a small number of purchases.

Another consideration is the circumstances in which the members of a queue join and leave it. They may have come from a different queue and may be going on to still another one, so that the queues are connected in a network with each one affecting the others. Interconnected queues are often seen in the flow of paper work and the making of decisions in corporations and governments.

Queues seem to arise quite simply: the server cannot finish with every customer before more customers arrive, so that a waiting line builds up. The process nonetheless rewards closer examination. Consider a single queue with a single server, and suppose that members arrive at precise intervals and that each member requires the same amount of time to be served. The possibilities are readily apparent. If the time required for the performance of the service is less than the interval between the arrival of customers, each customer can be served immediately on arrival, and the server will even have a period of free time before the next customer appears. If the service time exceeds the interarrival time, the server is overtaxed. As he falls increasingly behind, a queue forms and grows. This would happen, for example, if the average time required for service were 30 seconds and new customers were arriving at an average interval of 25 seconds. The ratio of the service time to the interarrival time would be 6 : 5.

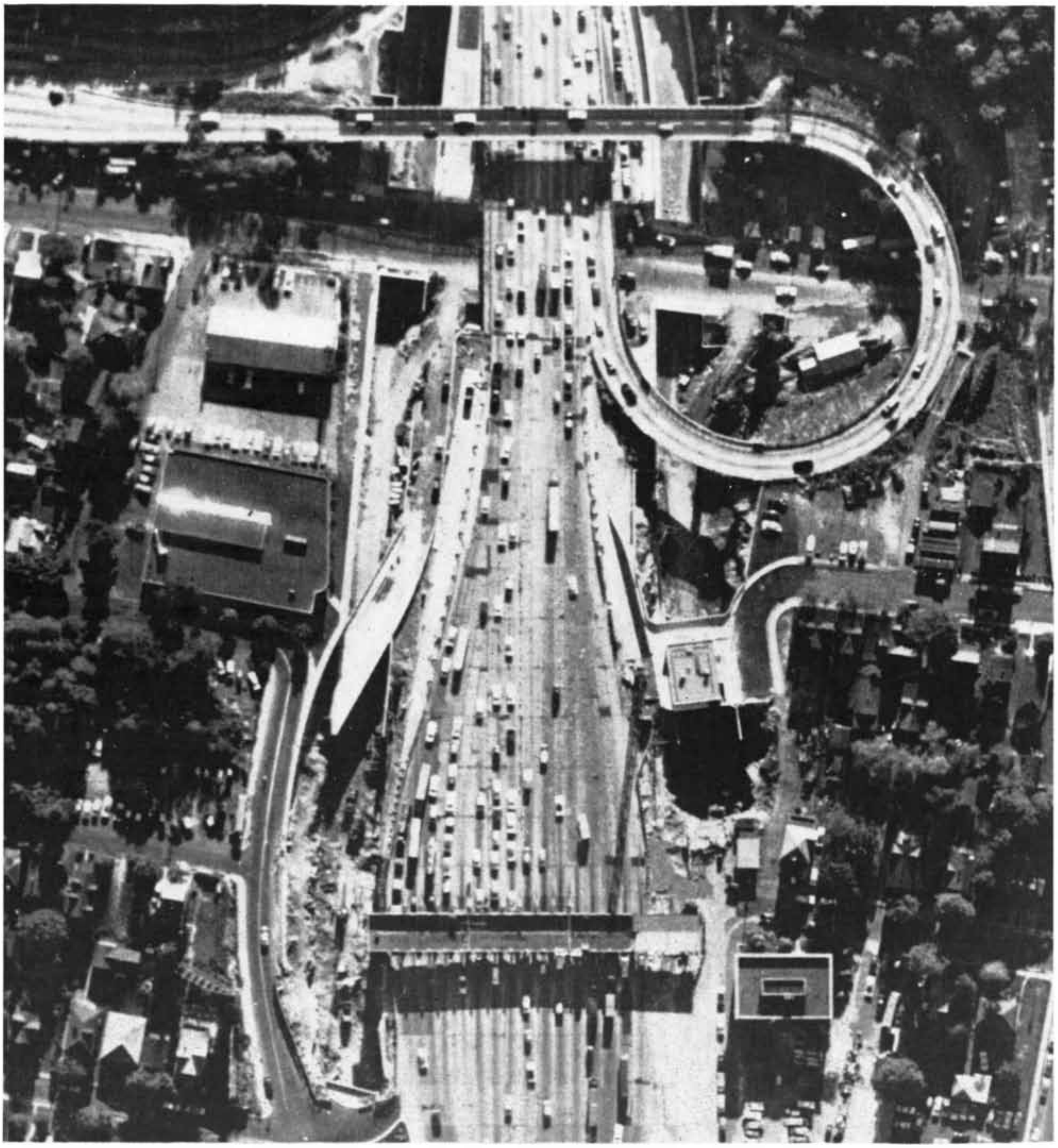
Such ratios are fundamental in the study of queues; they measure how extended the server is in meeting the demand. To put it another way, the ratio describes the density of the traffic with which the server must deal. In queuing theory the ratio is customarily expressed in a single number.

The critical value of the traffic density is clearly unity, or one. If the density is less than unity—that is, if the average service time is less than the average interarrival time—there is either no queue or a queue that is stable in the sense that it never becomes unduly long. If the traffic density is more than unity, a steadily growing and therefore unstable queue results.

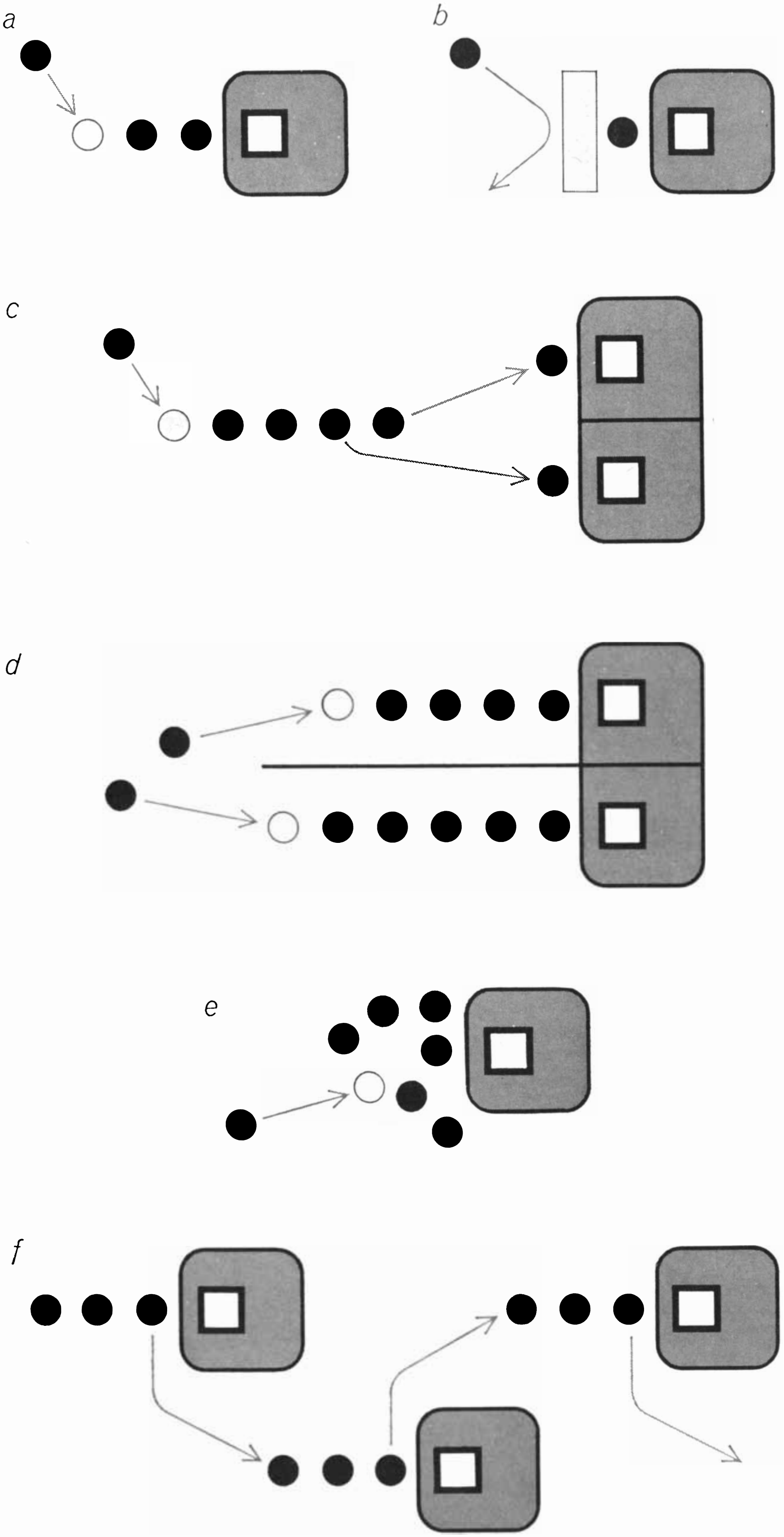
Imagine now a queue in which the

pattern of arrivals is not fixed. Instead queue members come in some random way, before or after an appointed time or without appointment. As the variations from a strict order increase it can occasionally happen that new members appear in such quick succession that they encroach on one another's service time. Finding the server occupied, they are obliged to wait in line. Accordingly for a while the traffic density seems greater than unity. The sharp influx will usually be balanced later by a period of abnormal calm in which the queue will shrink. If in addition to the randomness of the interarrival time the service time is also subject to random variations, the likelihood of fluctuations in the length of the queue will be even greater, since a surge of arrivals may consist of members requiring unusually long service times.

To the extent that the variations from strict order can be specified—that is, insofar as the nature of the randomness can be described—a mathematical foothold is provided for the analysis of queues. Random situations can be analyzed in terms of probability. Although one cannot say how many people will be in a queue at some future time, one can—



LENGTHY QUEUES build up during a peak traffic period at the tollbooths serving the George Washington Bridge between New York and New Jersey. The view is of the New Jersey side, which is the location of all the tollbooths at the bridge. Photograph was made by the Port of New York Authority when the bridge had only one set of tollbooths; additional booths now serve a lower deck.



TYPICAL QUEUING SITUATIONS include (*a*) a single queue with a single server; (*b*) the same situation except with no waiting allowed; (*c*) a single queue with two servers; (*d*) two servers with incoming customers divided randomly between them; (*e*) random order of service rather than the usual first-come-first-served order, and (*f*) interrelated queues.

given enough information about the pattern of arrivals—calculate the probability that there will be a given number. Similarly, one cannot say precisely how long a member of a queue must wait for service, but one can predict the probability that he will have to wait longer than a given amount of time.

When the pattern of arrivals and service times is completely random, which is to say that all semblance of order has disappeared, the probabilities as to the interval of time between arrivals and the amount of time needed for service follow what is called the exponential law. The significance of this fact is that the probability of a person's arriving at the queue or finishing his service does not depend in any way on when the last person arrived or when he finished receiving his service. In other words, the probability is completely independent of the past history of the system. The fact that the probabilities in many applications often follow the exponential law is fortunate for queuing theory, because it results in a drastic simplification of what would otherwise be a difficult mathematical analysis.

The impact of this simplification for any queuing system is felt when one undertakes to represent the state of the system, that is, to give a set of variables that describes the system. These variables must also be such that, given their values at any time, their future behavior can be predicted. Were it not for the exponential law, one could not establish the probability of change in the length of a queue without knowing when the last member of the queue had arrived and when the first one had begun to receive service. When the interarrival and service times obey the exponential law, however, one does not need to know such facts. The state of the system can be described simply by the probability that the queue will be of any given length.

Consider now the queue exemplified by a one-car parking lot. With no waiting allowed, the queue contains either one member—the one who is being served—or none. It could also be said that the server is busy or idle, according to whether the lot is occupied or empty. It is interesting to trace how the probability that the server will be idle varies as time passes. Assuming that he is idle initially, the probability will start at unity, or a maximum, and will decrease—rapidly at first, with the growing likelihood that a customer will arrive, and then more slowly, finally approaching some fixed number [*see top illustra-*

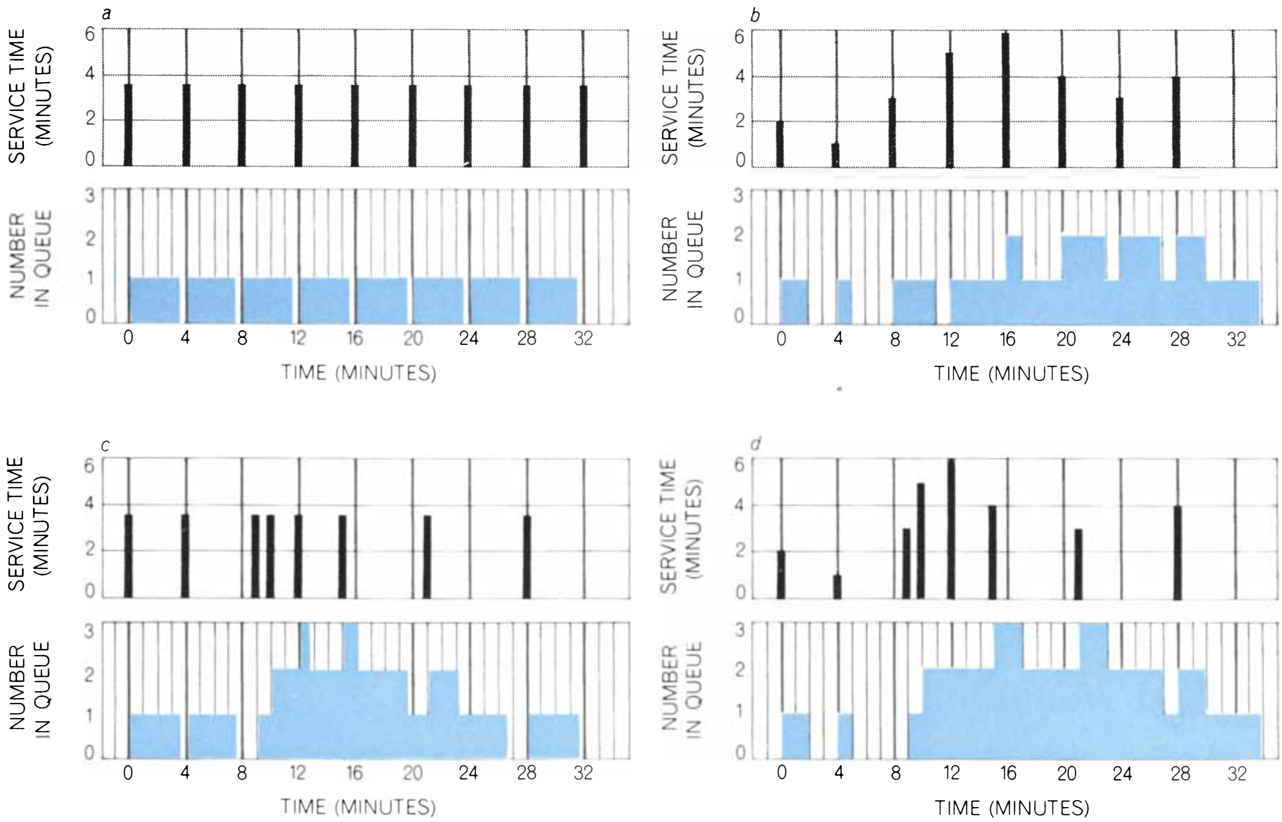
tion on next page]. The same number will be approached, but from the opposite direction, if the assumption is made that the server is initially busy.

As members of the queue come and go, the queue seems to "forget" its initial state. Ultimately the probability that the lot will be empty depends only on the traffic density—on how often, on the average, prospective members of the queue arrive compared with the rate at which they can be served. The probability is called stationary, because once it is reached it remains constant with time. The empirical meaning of the stationary probability is this: If a very large number of queues, identical in operation with the one considered here, were observed at some instant, the stationary probability would represent the fraction of them found empty. In practice, however, one is concerned with the behavior of a single queue over a period of time rather than with many queues at a single moment. There is a class of mathematical theorems, grouped together as the "ergodic theorem," that allows one to relate the single queue over a period of time to many queues at a given instant. The theorems state simply that the stationary probability is not only the fraction of queues that will be found empty at any instant but also the fraction of time that any given queue will be empty. It is as if this one queue during its life mirrors all queues like it.

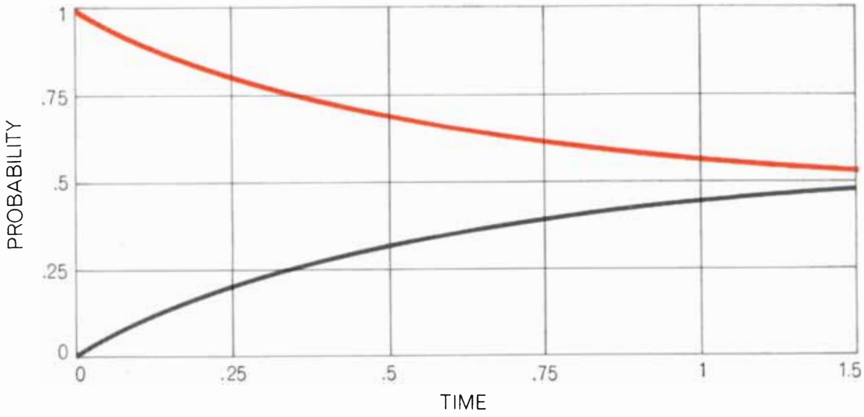
By removing all restrictions on the number of queue members that may wait, one comes to the queue of arbitrary length—what investigators of queues call the "infinite-queue case." It is not difficult to find the stationary-state probabilities of such a queue and to derive from them the average queue length. As the traffic density nears the critical value of unity it is startling to observe how rapidly the average queue length grows [*see bottom illustration on next page*]. Growing with it is the average waiting time, which includes the service and which therefore is directly proportional to the average queue length because each member of the queue must wait for everyone in front of him to be served.

It appears that when the queue is operating near the limits of stability, an arrival rate or service load only slightly larger than normal will for a short time produce an unstable traffic density. This happens frequently under the wide variations allowed by the exponential law. The average busy period—the time when the server is continuously occupied—has the same character. This is a significant consideration when there is a limit on how long a server can function without rest or repair.

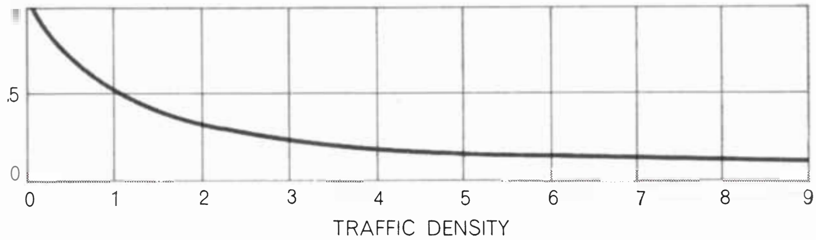
Yet even when the average queue length has reached the high value of 19 (a number resulting from a traffic density of .95), the server will be idle 5 percent of the time. This relatively simple case typifies a general problem confronted by the systems planner—a problem that is caused by the random pattern of service time and interarrival time. Keeping the traffic density low will reduce queue lengths and waiting times, but it means substantial periods of idleness and nonproductivity for the server. On the other hand, decreasing the service capacity—that is, allowing the traffic density to be large—results in the service system's being more fully utilized and in that sense more efficient, but it also implies more crowding, longer waits and the



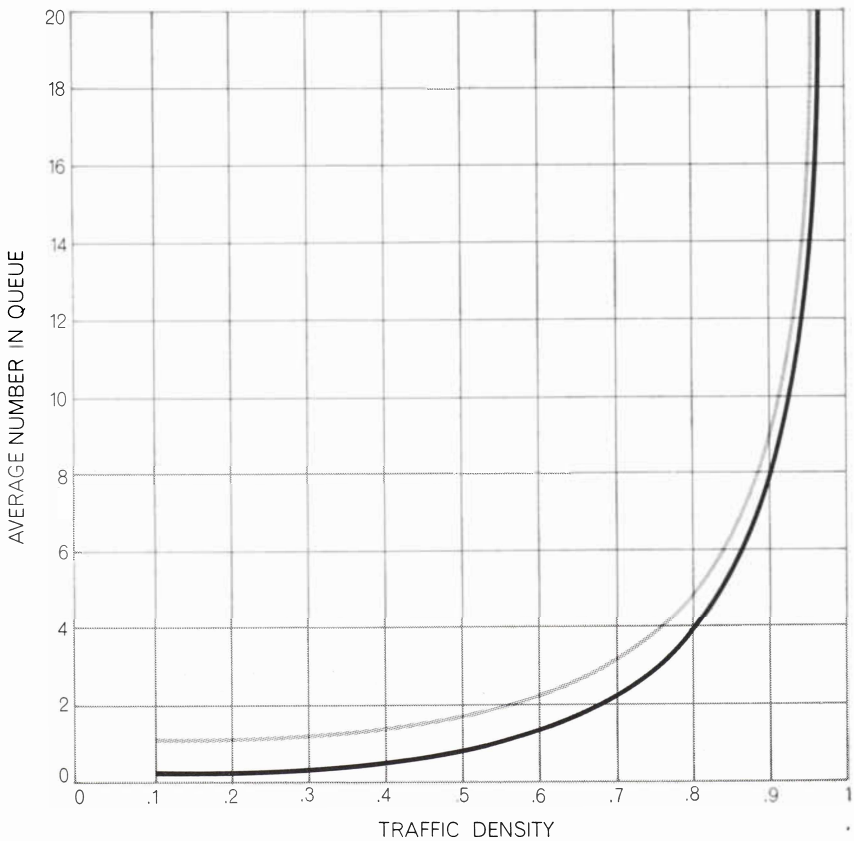
BUILDUP OF QUEUES results from the variability of the time between the arrival of one customer and the next one and of the time required to serve customers. Each of these illustrations shows at top the frequency with which customers arrive and the length of time required to service them and at bottom the resulting variations in queue size. In each case the average time between arrivals is four minutes and the average service time is three and a half minutes. The situations shown are (*a*) interarrival and service times fixed; (*b*) interarrival times fixed, service times variable; (*c*) interarrival times variable, service times fixed; (*d*) both variable.



CURVES OF PROBABILITY that a queue in which no waiting is allowed will be empty vary according to whether the queue is initially empty (*top*) or initially full (*bottom*). In time each curve approaches the same value, which is called the stationary probability.



STATIONARY PROBABILITY is a function of the traffic density, which is the ratio of the average time required to provide service to a customer and the average interval of time between the arrival of customers. Traffic-density ratios are fundamental in queuing studies.



RAPID LENGTHENING of a queue occurs with rising traffic density. Increasing with average queue length (*black*) is average number of people served during a busy period (*gray*).

possibility that members of the queue may be turned away or that they will leave. Such a situation is of course undesirable for those engaged in competitive business.

How, then, should these conflicting requirements be balanced? No single answer can be given. The level of service that should be provided depends on the nature of the service. If the service is designed to respond to emergencies, as it is in fire and police departments, anything short of immediate availability can be undesirable and even dangerous. A high level of service is a necessity.

If the service is more routine, as it is in transportation and telephone systems, the problem is to weigh the costs of congestion and delay against the costs the public is willing to bear for improved facilities. The ultimate solution for such service involves considerations that transcend queuing theory. Nonetheless, queuing theory provides valuable assistance in reaching a solution, because it is a means of assessing the various alternatives quantitatively and thereby makes possible a rational decision rather than an intuitive one.

If a decision to make queues shorter has been reached, it is instructive to compare various possibilities. Let us consider a queue in which there is one server and it has been decided to double the service capacity. The most obvious solution is to reduce the service time by half. This solution may not be feasible, however, if the server does not come in a range of speeds, as is the case in most queues where the server is a person. A second solution is to have two servers working from a common queue. Third, one can have two servers but can separate them so that arriving queue members are distributed randomly between them.

It turns out that the first solution, when it can be adopted, is the most effective, and that both the first and the second solution are superior to the third one [*see illustration on opposite page*]. If the traffic density is small, the first method results in average queue lengths that are only half the size of those yielded by the second method. Indeed, with the traffic density low it is rare to have more than one member in the queue, and he will be served more than twice as rapidly under the first solution as he would under the second one.

The reason the third method is the least satisfactory is that one of the two queues arising under this method may be congested while the other is empty. Because the two servers are separated no advantage can be taken of the idle server,' whereas when two servers are working from a common queue both are available at all times. A general principle is evident here: The best way to combat the random fluctuations that queues present is to seek maximum flexibility in the service arrangements.

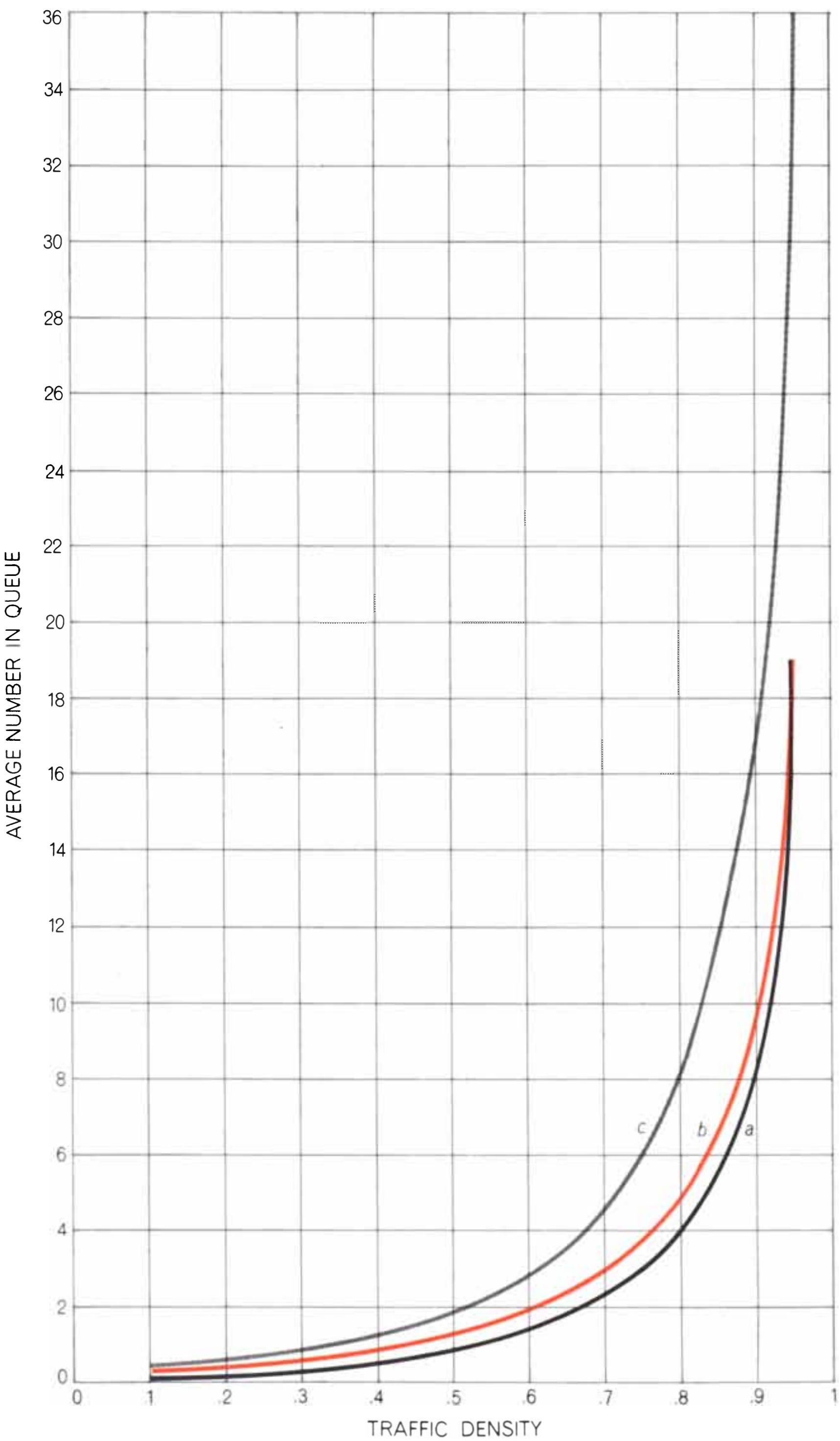
In certain situations the convenience of having servers in separate locations may more than offset the efficiency of centralization. An instance is the rental of automobiles. The example also illustrates the kind of difficulty that can be encountered with separated servers. Profitable operation requires that the number of unrented cars be kept low. At the same time demands originate from many widely separated points, and because of intense competition the demands must be met. The rental agencies often can cope with this situation only by a wasteful shuttling of unrented cars from city to city.

The most direct way of attacking the problem of overlong queues is through the basic cause of the problem: the random variations in service and interarrival times. The potential savings are substantial. Merely by making the service time the same for each member of the queue, the average queue length will be cut nearly in half at the large traffic densities. If in addition the interarrival times are made constant, the queue will simply be eliminated except for the member receiving service. Indeed, any move toward reducing random variations will usually produce a degree of improvement in the queue. Such moves have a price, however; it is measured in terms of restrictions on freedom or convenience. Often the price is too high for the result.

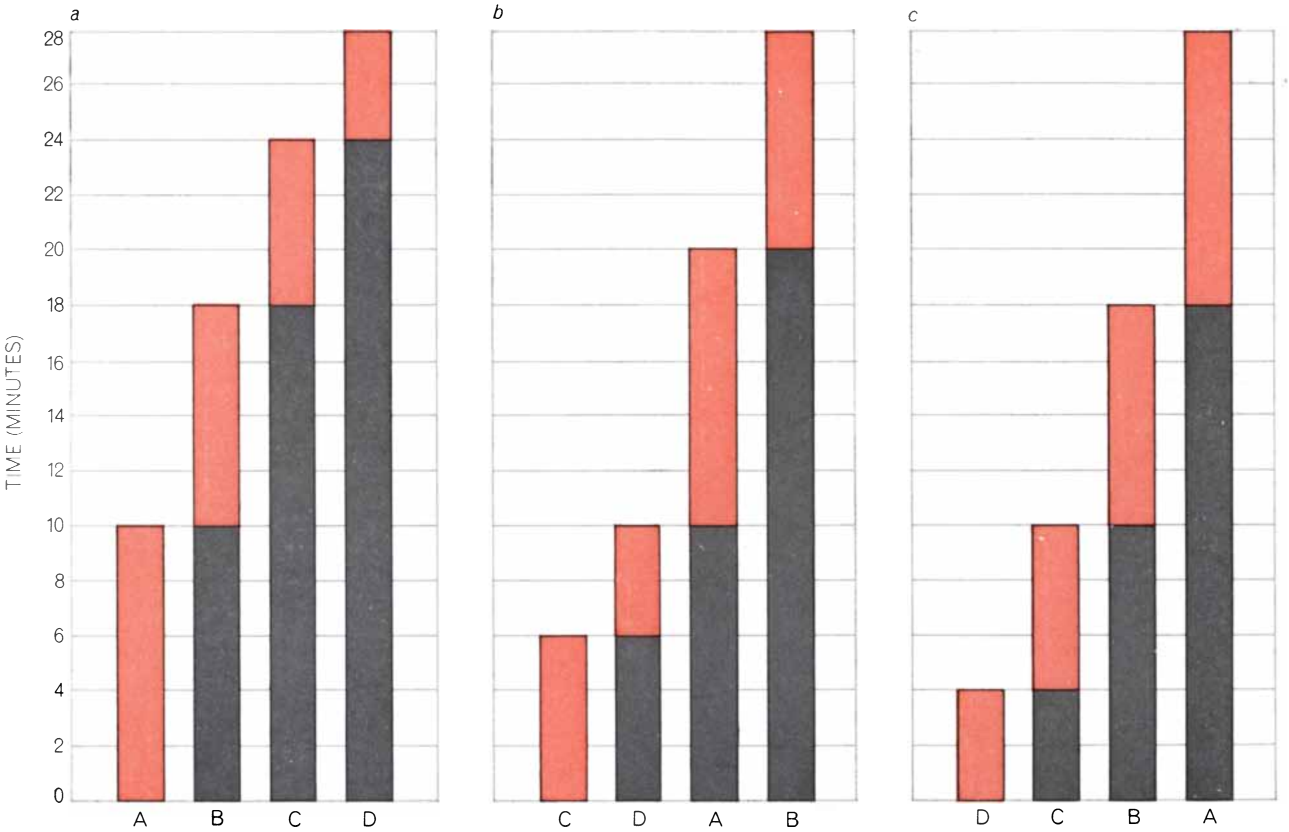
An arbitrary, unintelligent handling of a queue can also be costly. A familiar example is the random order of service known to everyone who has endured a holiday shopping jam at a department store or tried to get a taxi at a busy place. The queue lengths and average waiting times are unaffected, remaining the same as they are in the normal first-come-first-served case, but the new element of chance introduced by the lack of service discipline makes individual variations in waiting time much larger than they would be otherwise. For everyone who is able to congratulate himself on receiving quick service there will be many others who are frustrated and angered by the slow service. Some stores have tried to avoid such reactions by issuing numbers to customers as they arrive.

One effective way of reducing queues is to serve the members of the queue in a selective order. Here we touch on the broader subject of priorities in queues. Priorities are instituted when it is desirable to serve certain members of a queue sooner than other members for reasons such as dealing with emergencies or reducing costly waiting time.

Suppose a queue is divided into a number of ordered classes, with members of a given class being served in order of their arrival but always sooner than any members of a lower class and



DOUBLED CAPACITY for providing service to customers can be achieved in various ways with varying effects on the average length of the queue. Here the effects are shown of doubling the service capability by (*a*) cutting the service time in half; (*b*) having two servers working from one queue, and (*c*) having two queues with customers distributed randomly.



SYSTEM OF PRIORITIES can reduce the average waiting time of members of a queue. In a four-person queue (*a*) whose members are served in order of their arrival, the average waiting time is 20 minutes. Member *B*, for example, has to wait for the 10 minutes required to serve *A* plus the eight minutes required for his own service. If *C* and *D*, who have shorter service times, are given priority (*b*), the average waiting time is reduced to 16 minutes. If members are served strictly in order of the time required for service (*c*), with the member who can be served the most quickly being served first and so on, the average waiting time is reduced to 15 minutes.

later than members of a higher one. It is possible to distinguish two types of priority, preemptive and nonpreemptive. A priority is preemptive if the arrival of a member of a higher class immediately interrupts service to a member of a lower one. The priority is nonpreemptive if the service to a member of a lower class is allowed to go to completion before the service to an arriving member of a higher class begins.

An example of preemptive priority is a queue served by a machine that is subject to breakdown. A breakdown can be regarded as the arrival of a member of higher priority. The service time for that member is the length of time it takes to repair the machine. Meanwhile the members of the lower class—the group ordinarily served by the machine—are left without service.

With preemptive priorities the presence of members of a lower order has no effect on the higher order—either on the length of its queue or the waiting time of its members. A nonpreemptive priority can have a small effect on the higher order, resting on the possibility that a member of the higher order arrives while a member of the lower order is being served. In both instances it is quite possible for the queue of members of the higher class to be quite small while the queue of members of the lower class is very large and even unstable.

Imagine now that priorities are assigned according to service time. All the members whose service time is less than a certain figure are placed in one class, and all other members go into a lower class. One can find an optimal division to minimize the average wait and can compute the resultant saving [*see illustration above*]. As can be seen from the illustration, the saving is substantial when the traffic is large.

One need not stop at two classes. Indeed, further division will continue to reduce the average wait until ultimately the queue is served strictly in order of service time. Priorities do have their limits. Institutions such as banks and supermarkets, serving the public directly, tend to avoid the establishment of elaborate priorities because it may offend some customers. They may, however, undertake an indirect and limited form of priority by means of the express-lane device, which provides a form of special service for customers whose demands can be met quickly.

Another scheme of priorities is often employed with computers that are operated on a shared-time basis, in which the computer must deal with demands arriving randomly from a number of different users. The scheme involves serving a demand in order of its arrival and for a certain fixed time. If the service has not been completed within that time, the computer goes on to the next user and the unfinished part of the previous demand is put at the end of the queue.

To sum up, one can reduce the length of queues by increasing the capacity of the server or by establishing an order in which members of the queue are served. Between the two methods there is a significant distinction. The capacity of a server can be increased before the queuing system has begun operation. Establishing an order of service means that the server must be continually aware of what is happening in the queue and must act accordingly.

The second technique is a dynamic method of control and the first one is a static method. The dynamic approach is based on more information—the actual behavior of the queue rather than the predicted behavior—and so is potentially the more effective method, particularly in meeting unforeseen changes. Modern computers have made such methods feasible and in some instances, such as traffic control, a reality, even though the relevant mathematical theory is only in an early stage of development.

Queuing theory was founded by the work of A. K. Erlang, who began in 1908 to study problems of congestion in telephone service for the Copenhagen Telephone Company. Since then workers in the field have tended to concentrate on describing fairly uncomplicated situations, involving at most a few queues. It seems likely that the pressures of a rapidly advancing technology will direct the attention of queuing theorists increasingly toward the analysis of systems containing many interacting queues. Such systems include the national and international telephone networks; large computers dealing with a variety of users or problems, and traffic-control systems covering wide areas.

The complexity of such systems defies exact mathematical analysis. The systems will require essentially new ideas if they are to be fully understood. I believe a source of inspiration can be found in the many-body theories that underlie so much of modern physics as ways of describing highly complex interacting systems such as the molecules in a gas.

In this context I should like to discuss what is called in queuing theory "the polling problem." Consider a large number of queues, each with its own input, served cyclically by a single server. The server goes from one queue to the next, taking a certain amount of travel time in the process, and serves everyone in a queue before proceeding to the next queue. A commonplace example would be a bus that stops at various places to load and unload passengers while it plies a circular route.

My interest was stimulated by a different application, in which the server is a computer. It cyclically polls a number of remote terminals to ascertain what demands have arrived since its last visit. This is the mode of operation in many time-shared systems.

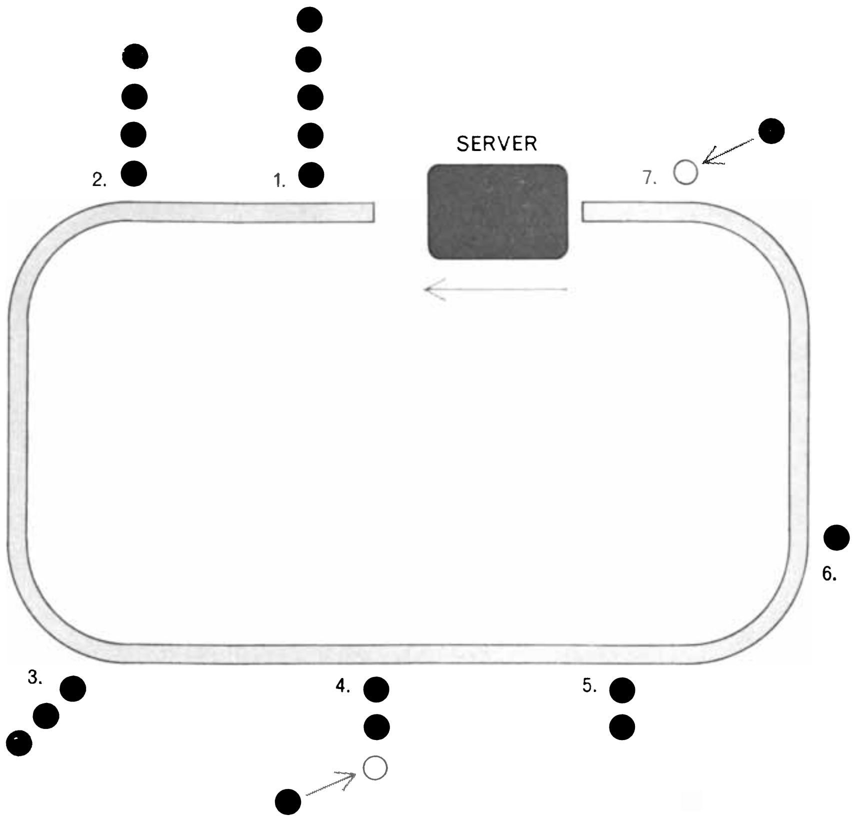
The quantities that could be used to define the state of such a system are the probabilities that there will be jointly a given number of members in the first queue, the second one and so on. Such detailed information, however, is usually not only unobtainable but also unnecessary. It would ordinarily be sufficient if one could ascertain the probability that a certain number of members will be in any single queue, but it is impossible to obtain even such a partial description of the system without first obtaining a complete description. One therefore needs a suitable approximate model.

In studying this problem my colleagues and I have come on an approach that appears promising. The key idea is to assume first that the queues are independent. Therefore the probability that the server will encounter a certain number of members at a given queue defines a state.

One now makes the assumption that the same state is met by the server at every other queue. Since the state, which relates to the number of members in a queue, affects the time needed for the server to make the circuit of the system, the state ultimately defines that time. The final assumption is that the state is self-consistent, so that when the server returns to his starting point, he finds the queue there has regenerated itself into the same state it had on his first visit. The concept of a self-consistent state plays, in an analogous way, an important role in the physics of many-body systems.

This approach can be called microscopic because it focuses on a single one of several interacting queues. It is encouraging to compare the results obtained by this method with those found by exact calculation in the case of two queues. The results agree closely, particularly in cases where the traffic density is low.

To complement such a microscopic approach it is possible to conceive of a macroscopic theory. Such a theory would attempt to describe a large network of queues by a few quantities pertaining to the entire system. It would be as if the network were being observed from a considerable distance, so that its individual elements were a blur but the behavior of the system as a whole was apparent. Several investigations of such an approach are now in progress.



POLLING TECHNIQUE involves queues that interact with one another. A single server, such as a bus plying a circular route or a computer polling the terminals in a shared-time arrangement, serves several queues in a cyclical order. The queues interact because an unusually long one delays the server and causes the other queues to tend to be longer too.

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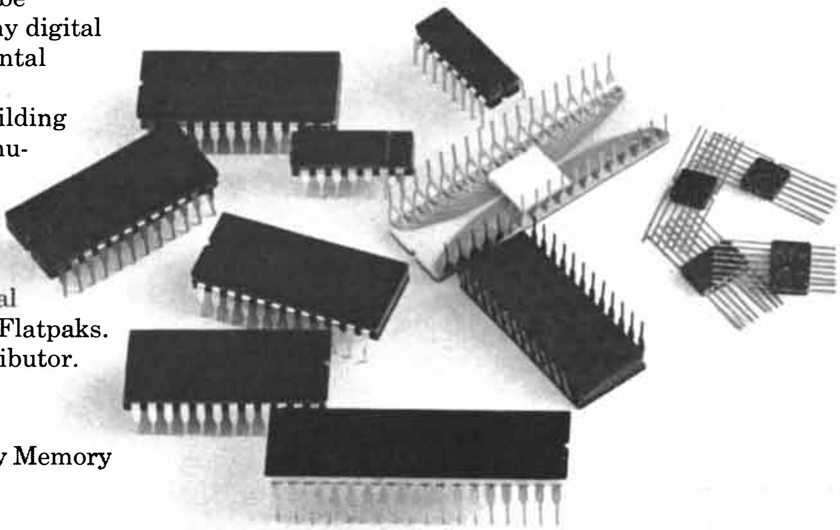

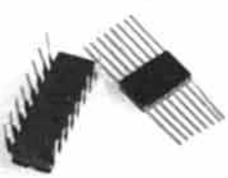

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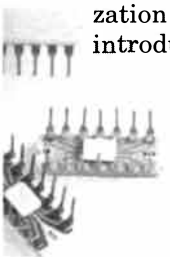

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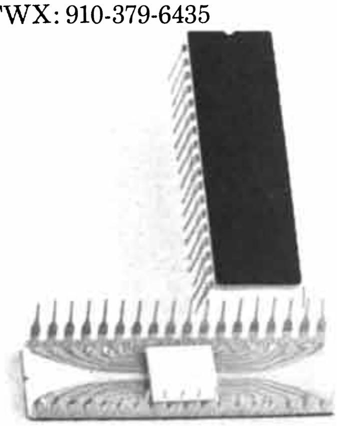


MATHEMATICAL GAMES

An array of puzzles and tricks, with a few traps for the unwary

by Martin Gardner

Instead of the usual eight or nine short problems presented occasionally in this department, we give this month a collection of "quickies," none of which requires advanced mathematics and most of which involve amusing catches or surprising twists. The reader is urged to take only some of them seriously, but to do his best to solve each one before going on to the answers, which follow the problems.

1. A farmer has three pink pigs, four brown pigs and one black pig. How many pigs in this set of eight can say they are the same color as another pig in the set?

2. In a certain African village there live 800 women. Three percent of them are wearing one earring. Of the other 97 percent, half are wearing two earrings, half are wearing none. How many earrings all together are being worn by the women? Solve in your head.

3. Each face of a convex polyhedron can serve as a base when the solid is placed on a horizontal plane. The center of gravity of a regular polyhedron is at the center, therefore it is stable on any face. Irregular polyhedrons are easily constructed that are unstable on certain faces; that is, when placed on a table with an unstable face as the base, they topple over. Is it possible to make a model of an irregular polyhedron that is unstable on *every* face?

4. What is the missing number in the following sequence: 10, 11, 12, 13, 14, 15, 16, 17, 20, 22, 24, 31, 100, ——, 10000, 1111111111111111. (Hint: The missing number is in the ternary system.)

5. Arrange 16 pennies in a square formation [*see illustration at left below*], alternating heads and tails. By touching no more than two pennies, rearrange the matrix so that each horizontal row of four is either all heads or all tails.

6. A logician with some time to kill in a small town decided to get a haircut. The town had only two barbers, each with his own shop. The logician glanced into one shop and saw that it was extremely untidy. The barber needed a shave, his clothes were unkempt, his hair was badly cut. The other shop was extremely neat. The barber was freshly shaved and spotlessly dressed, his hair neatly trimmed. The logician returned to the first shop for his haircut. Why?

7. A single cell is added to a ticktacktoe board [*see middle illustration below*]. Can the first player always win?

8. A secretary types four letters to four different people and addresses the four envelopes. If she inserts the letters at random, what is the probability that exactly three letters will go into the right envelopes?

9. Consider these three points: the center of a regular tetrahedron and any two of its corner points. The three points are coplanar (lie on the same plane). Is this also true of all *irregular* tetrahedrons?

10. Solve the crossword puzzle at the right below with the help of these clues:

Horizontal
1. Norman Mailer has two.
2. Is indebted.
3. Chicago vehicles.
4. Relaxation.

Vertical
1. Skin blemish.
5. Works in the dark.
6. Character in *Wind in the Willows*.
7. Famous white Dixieland trombonist.

11. Three points are selected at random on a sphere's surface. What is the probability that all three lie on the same hemisphere?

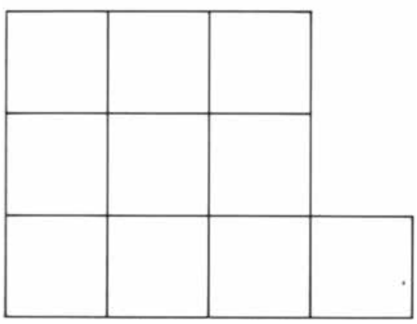
12. A man gave his wife for her birthday a diminutive aurum truncate cone, convex on its summit and semiperforated with symmetrical indentations. What did he give her?

13. If you took three apples from a basket that held 13 apples, how many apples would you have?

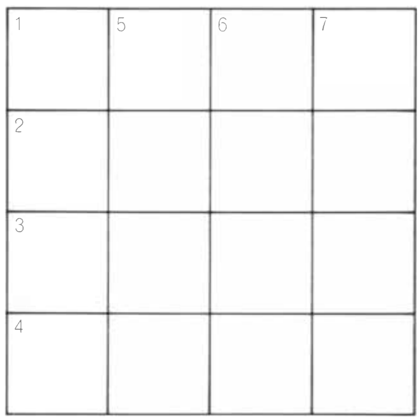
14. Two tangents to a circle are drawn [*see top illustration on opposite page*] from a point, C. Tangent line segments YC and XC are necessarily equal. Each has a length of 10 units. Point P, on the circle's circumference, is randomly chosen between X and Y. Line AB is then drawn tangent to the circle at P. What length is the perimeter of triangle ABC?

15. Nine thousand, nine hundred and nine dollars is written $9,909. How quickly can you write the figures for twelve thousand, twelve hundred and twelve dollars?

The 16-penny puzzle



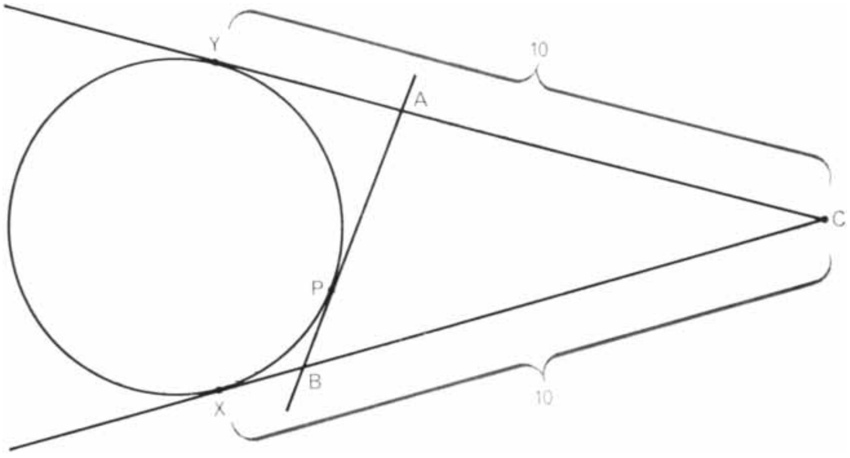
Modified ticktacktoe



Crossword puzzle

16. A chemist discovered that a certain chemical reaction took 80 minutes when he wore a jacket. When he was not wearing a jacket, the same reaction always took an hour and 20 minutes. Can you explain?

17. Each of the two paper structures shown at the bottom of this page has a horizontal band of the same length and width as its vertical band. The structures are identical except that the second has a half-twist in its horizontal band. If the first is cut along the broken lines, the surprising result is the square surrounding the two structures. What results if the second structure is similarly cut along the broken lines? (Answer before experimenting with a model.)



A tangent problem

18. An equilateral triangle and a regular hexagon have perimeters of the same length. If the triangle has an area of two square units, what is the area of the hexagon?

19. Can a $6 \times 6 \times 6$ cube be made with 27 bricks that are each $1 \times 2 \times 4$ units [*see top illustration on next page*]?

20. A customer in a restaurant found a dead fly in his coffee. He sent the waiter back for a fresh cup. After taking one sip he shouted, "This is the *same* cup of coffee I had before!" How did he know?

21. A metal sheet has the shape of a two-foot square with semicircles on opposite sides [*see illustration at left at bottom of next page*]. If a disk with a diameter of two feet is removed from the center as shown, what is the area of the remaining metal?

22. "I guarantee," said the pet-shop salesman, "that this parrot will repeat every word it hears." A customer bought the parrot but found it would not speak a single word. Nevertheless, the salesman told the truth. Explain.

23. Five chords and a tiny circle, drawn on a larger circle as in the middle illustration at the bottom of the next page, make a picture of something. But what?

24. From the same corner of a square with a side of three inches, extend two line segments that exactly trisect the square's area [*see illustration at right at bottom of next page*]. How long is each line segment?

25. A 10-foot piece of cylindrical iron pipe has an interior diameter of four inches. If a steel sphere three inches in diameter is inserted into the pipe at end *A* and a steel sphere two inches in diameter is inserted at end *B*, is it possible, with the help of a rod, to push each sphere through the entire length of pipe so that it emerges at the other end?

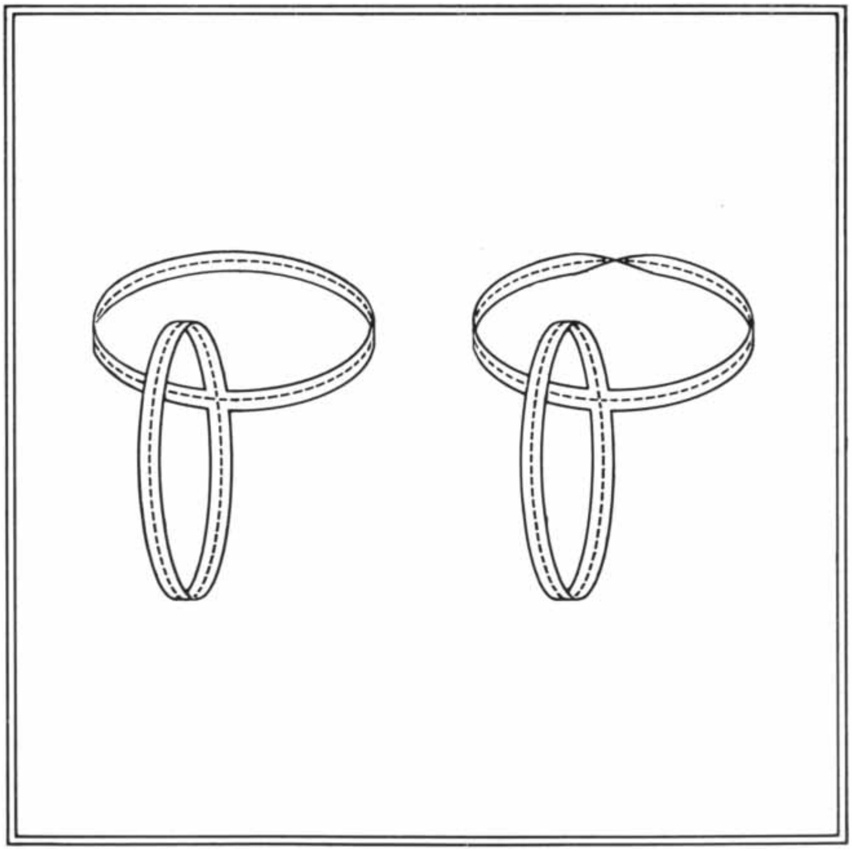
26. Give at least three ways a barometer can be used to determine the height of a tall building.

27. How can you make a cube with five paper matches? No bending or splitting of matches is allowed.

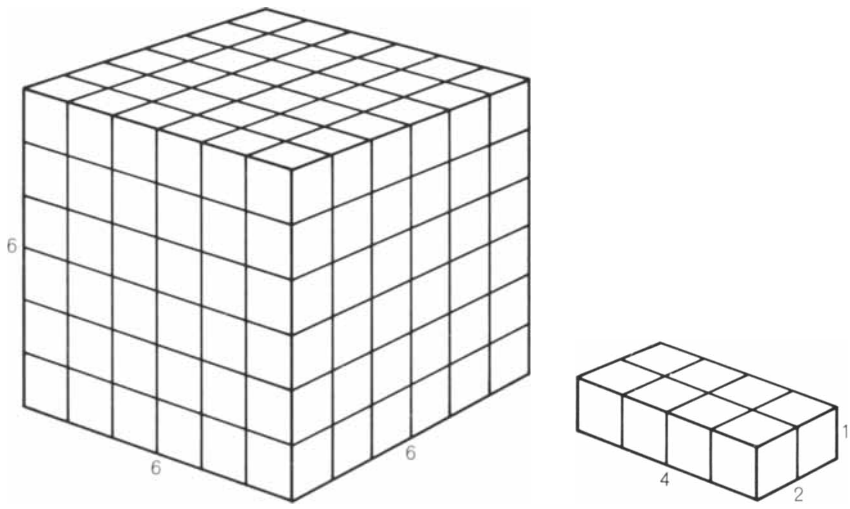
28. A gift package with sides of five, six and 13 inches is bound with an endless elastic ribbon in the familiar fashion [*see upper illustration on page 109*]. The pairs of ribbon segments crossing the top and bottom of the package are parallel, the other four segments are vertical, and each of the eight points where the ribbon passes over an edge is the same distance *AB* from the nearest corner. What distance *AB* minimizes the ribbon's total length?

29. Which situation is more likely after four bridge hands have been dealt: you and your partner hold all the clubs or you and your partner have no clubs?

30. This old-timer still confuses almost everyone who hears it for the first time. Smith gave a hotel clerk \$15 for his room for the night. When the clerk discovered that he had overcharged by



A topological question



Cube-dissection puzzle

$5, he sent a bellboy to Smith's room with five $1 bills. The dishonest bellboy gave only three to Smith, keeping the other two for himself. Smith has now paid $12 for his room. The bellboy has acquired $2. This accounts for $14. Where is the missing dollar?

31. Among the assertions made in this problem there are three errors. What are they?

a) $2 + 2 = 4$
b) $4 \div \frac{1}{2} = 2$
c) $3\frac{1}{5} \times 3\frac{1}{8} = 10$
d) $7 - (-4) = 11$
e) $-10(6 - 6) = -10$

Answers

1. None. Pigs can't talk.

2. Among the 97 percent of the women, if half wear two earrings and half none, this is the same as if each wore one. Assuming, then, that each of the 800 women is wearing one earring, there are 800 earrings in all. (Thanks to L. Vosburgh Lyons.)

3. No. If a convex polyhedron were unstable on every face, a perpetual motion machine could be built. Each time the solid toppled over to a new base it would be unstable and would topple over again. (Thanks to Richard Guy.)

4. Each number is 16 in a number system with a different base, starting with base-16 and continuing with bases in descending order, ending with base-1. The missing number, 16 in the ternary system, is 121. (From Angela Dunn, *Mathematical Bafflers*.)

5. Put your first and second fingertips on the first and third pennies in the top row, slide them to the base of the square so that they touch the first and third pennies in the bottom row. Push up, moving the first and third columns upward to form a pattern with all tails in the first and third rows, all heads in the second and fourth.

6. Each barber must have cut the other's hair. The logician picked the barber who had given his rival the better haircut.

7. Yes. A corner opening in ticktacktoe leads to a win unless one's opponent takes the center. A first X play as shown in the illustration at the lower left on the opposite page must be met by O in the center to keep the first player from winning even if there is no 10th cell. But now the first player can make his second move as shown, which leads to an obvious win on his next move.

8. Zero. If three letters match the envelopes, so will the fourth. (From Charles Trigg, *Mathematical Quickies*.)

9. Yes. *Any* three points in space are coplanar.

10. The solution to the crossword puzzle is shown at the lower right on the opposite page.

11. The probability is certainty. Any three points on a sphere are on a hemisphere.

12. A gold thimble.

13. Three apples.

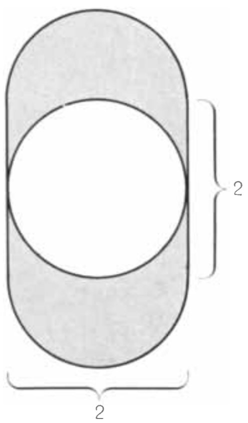
14. The triangle's perimeter is 20 units. Lines tangent to a circle from an exterior point are equal, therefore $YA = AP$ and $BP = XB$. Since $AP + BP$ is a side of triangle ABC, it is easy to see that the triangle's perimeter is $10 + 10 = 20$. This is one of those curious problems that can be solved in a different way on the assumption that they have answers. Since P can be anywhere on the circle from X to Y, we move P to a limit (either Y or X). In both cases one side of triangle ABC shrinks to zero as side AB expands to 10, producing a degenerate straight-line "triangle" with sides of 10, 10 and 0 and a perimeter of 20. (Thanks to Philip G. Smith, Jr.)

15. $13,212.

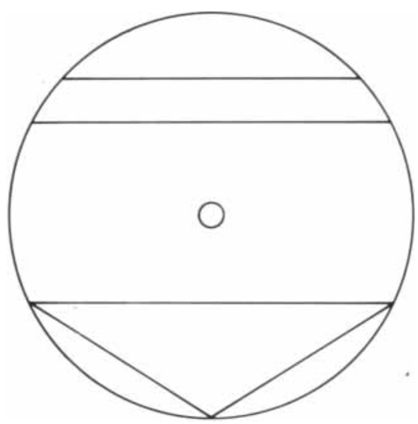
16. Eighty minutes is the same as one hour and 20 minutes.

17. Cutting the second structure produces the same result as cutting the first. (Thanks to Michael Stolnicki.)

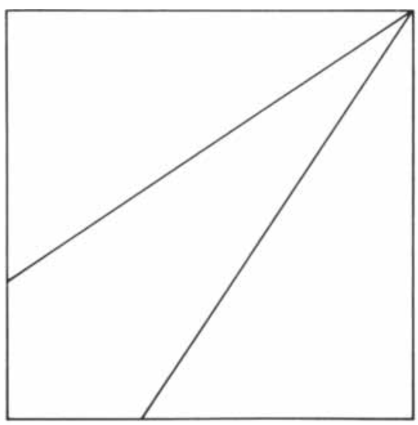
18. Three square units [*see upper il-*



Hole-in-metal problem



Mathematical droodle



Trisecting the square

lustration on page 111]. (From Charles Trigg, *Mathematical Quickies*.)

19. No. Think of the order-6 cube as made up of 27 cubes with sides of two units and alternately colored black and white. Since 27 is an odd number there will be 13 cubes of one color and 14 of another. No matter how a brick is placed within this cube, half of its unit cubes will be black and half white, so that if the cube can be formed, it must contain as many black unit cubes as white. This contradicts the fact that the large cube has more unit cubes of one color than of the other, therefore there is no way to build the order-6 cube with the 27 bricks. (From M. H. Greenblatt, *Mathematical Entertainments*.)

20. The customer had sugared his coffee before he found the dead fly.

21. The two semicircles together form a circle that fits the hole. The remaining metal therefore has a total area of four square feet.

22. The parrot was deaf.

23. A navel orange wearing a bikini. (From Roger Price, *"The Rich Sardine" and Other New Droodles*.)

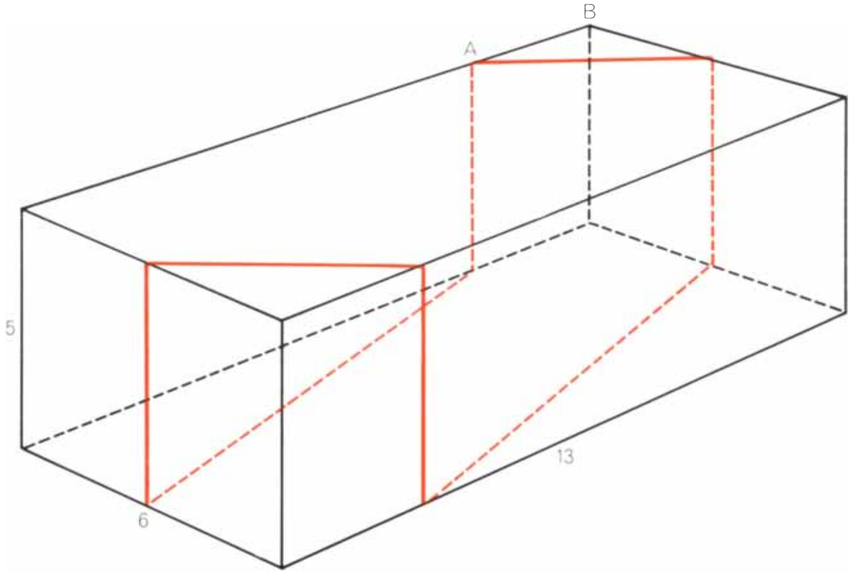
24. The square's area is nine square inches, therefore each trisecting line forms a right-angled triangle with an area of three square inches. Since the long side of each triangle has a length of 3, its other side must be 2 and its hypotenuse $\sqrt{13}$. Each hypotenuse is a trisecting line, therefore each line is $\sqrt{13}$ in length. (Thanks to Piet Hein.)

25. Yes, if the two spheres are pushed through the tube at different times.

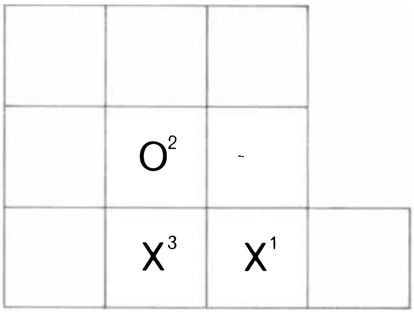
26. Here are five: (1) Lower the barometer by a string from the roof to the street, pull it up and measure the string. (2) Drop it off the roof, note the time it takes to fall and compute the distance from the formula for falling bodies. (3) On a sunny day, find the ratio of the barometer's height to the length of its shadow and apply this ratio to the length of the building's shadow. (4) Take barometer readings at the base and the top of the building and compute the height from formulas relating altitude and barometric pressure. (5) Find the superintendent and offer him the barometer if he will tell you the height of the building. (Thanks to Alexander Calandra.)

27. If "cube" is taken in the numerical sense, the five matches can be used to form 1 or 27, or the Roman numeral VIII. If the bottoms of the matches are straight, the arrangement shown in the lower illustration on page 111 produces a tiny cube at the center. (Thanks to Thomas Ransom for the VIII solution and to Mel Stover for the geometric one.)

28. *AB* can be any length from 0 to 13 because the ribbon's total length is constant no matter where *B* is. (From Hugo Steinhaus, *One Hundred Problems in Elementary Mathematics*.)



How is the ribbon's length minimized?



Ticktacktoe solution

M	M	M	M
O	O	O	O
L	L	L	L
E	E	E	E

Answer to crossword puzzle

29. The probabilities are the same. If you and your partner have no clubs, all the clubs will have been dealt to the other two players.

30. Adding the bellboy's \$2 to the \$12 Smith paid for his room produces a meaningless sum. Smith is out \$12, of which the clerk has \$10 and the bellboy \$2. Smith got back \$3, which, added to the \$12 held by the clerk and the bellboy, accounts for the full amount of \$15.

31. Only equations *b* and *e* are false, therefore the statement that there are three errors is false. This provides the third error. (Thanks to Epimenides the Cretan.)

Last month's problem was to find the rule for the cyclic ordering of the 10 digits in 7480631952. Start at the left and spell *zero,* counting one digit for each letter. The spelling ends on 0. Cross it out. Continue with *one*. Cross out 1. Proceed in this manner, spelling the digits in order from 0 through 9, counting only the digits that have not already been crossed out. The series is circular; if a count is uncompleted at the end of the line of digits, go back to the beginning. The arrangement makes it possible for all 10 digits to be spelled in numerical order.

Sets of playing cards can be similarly arranged so that each card can be spelled by moving cards singly from the top to the bottom of a packet, discarding the card that turns up at the end of each spelling. It is easy to construct such arrangements simply by time-reversing the procedure, taking the cards one at a time from a pile, in reverse order, and forming the packet in your hands by moving the cards singly from the bottom to the top of the packet for each letter. To test

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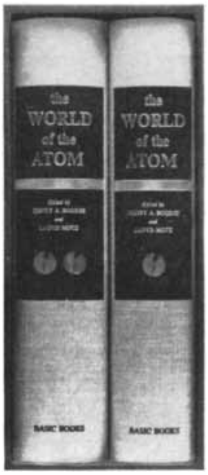

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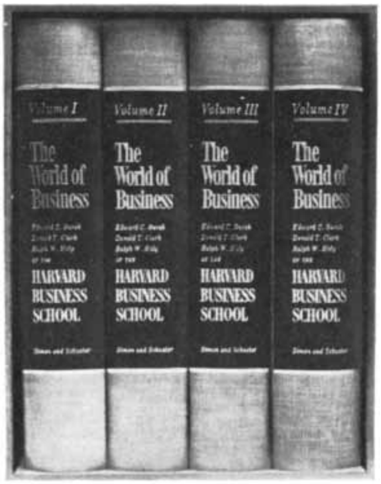

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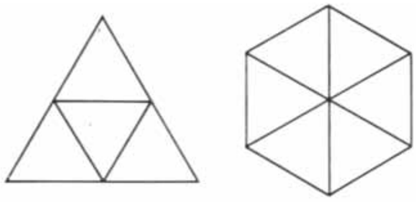
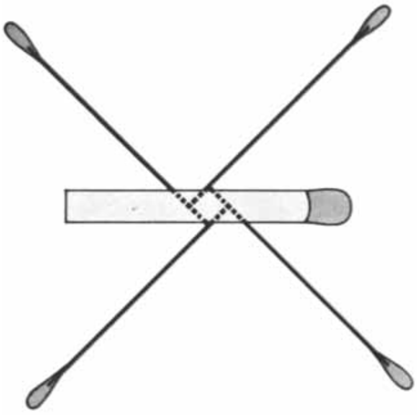


Triangle-hexagon solution



Five-match cube

this simple procedure the reader may enjoy arranging an entire deck so that every card can be spelled, starting with the Ace of spades and then proceeding with the two of spades and so on, the spades being followed by the other suits in a predetermined order, and ending with, say, the King of diamonds and the Joker.

In giving rules for the solitaire problem in June I assumed it was clear that any card played on a *B* column, either from the end of another *B* column or from a *T* cell, had to go on a next-higher card of the same suit unless it was used to fill an empty *B* space and start a new *B* column. By violating this rule when playing from a *T* cell to a *B* column, some readers easily achieved solutions in fewer than 54 moves. Most readers, however, interpreted the rules correctly and hundreds sent solutions in fewer than 54 moves. Many readers found 49-move solutions, the minimum received so far. Unless this is further reduced, I shall report next month a 49-move solution and the names of the readers who found such solutions.

I had said in June that all order-1 versions of the solitaire game were solvable, but Roger D. Coleman of Baltimore found a counterexample. The layout follows: first row, 6, J, A, 8, 9; second row, K, 4, 3, 7, 10; third row, Q, 5, 2. Only one move, a card to the single *T* cell, is possible.

THE AMATEUR SCIENTIST

Analyzing how a stone skips and turning sound into heat

Conducted by C. L. Stong

In April, 1957, Ernest Hunter Wright, the retired head of the Department of English at Columbia University, submitted to the readers of this department a puzzle that touched off an impressive amount of speculation. He observed that we all think we know what happens when we skip a stone on water. We believe it bounces over the water in a series of successively shorter leaps until it finally stops and sinks.

"I am fairly sure it does no such thing," Wright wrote. "I think a stone does not behave on water in the way described, because I *know* it does not on sand—the hard, wet sand at the water's edge....

"When I saw the marks left in the sand by my first pebble, I think I must have been as astonished as old Crusoe on beholding the first footprint of his man Friday! The first bounce of the pebble was only four inches long; the next was nearly seven feet; then came another short hop of only four inches; then a leap of about five feet; then again the four-inch hop, and so on for seven big hops punctuated by the four-inch ones. Each short hop was unmistakably recorded by two neat little marks in the sand. After the seventh repetition the pebble ceased this strange behavior and merely jumped along with successively shorter strides until it stopped. The total number of hops was about 20—my average on hard sand....

"Now I fancy the same thing happens on the water, though in the water there is no imprint left to tell the story. A proper record with a camera would give us the answer. In the sand, at least, the story is quite clear, and a very pretty story it is—as pretty as the tracks of some little animal in the fresh snow.

"As yet I have no explanation for these facts. I have put the problem before several physicists of high distinction, but so far have received no answer in return. Somewhere there must be an answer for my little riddle. Who will find it?... What scientist, professional or amateur, wants to go down to the beach with all the needful instruments and find the answer to my riddle? I shall be glad to go along if I am wanted; I can throw pretty well."

During the past 11 years more than 10,000 readers have submitted theories to this department that account in one way or another for the behavior of Wright's pebble, but no one has submitted the question to nature by inviting him down to the beach.

The puzzle has now been solved, by test. A few months ago Kirston Koths, a student at Amherst College, set up a synthetic beach in the laboratory and investigated the performance of stone disks by a series of nicely designed experiments. Koths writes:

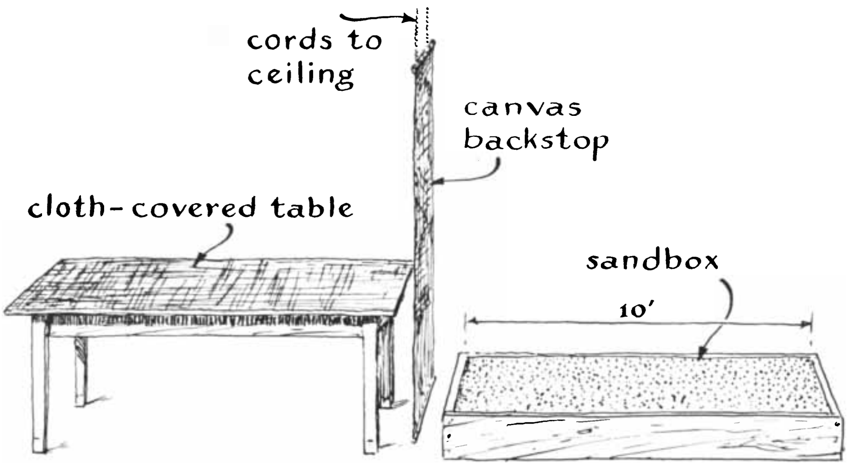
"I skipped the stone on surfaces of three types. They were a cloth-covered tabletop, water and sand. The plastic tabletop was covered with a woolen blanket and a thin layer of black cloth. This covering cushioned the stone's impact and resembled sand more than the bare tabletop did.

"The beach was simulated by a sandbox consisting of a rectangular frame of wood that was lined with a sheet of polyethylene, placed on the floor and filled with sand. An aluminum tray was used as a shallow tank for making experiments on water. A strip of canvas was suspended from the ceiling between the table and the sandbox as a backdrop to absorb the impact of the skipped stone.

"A stone of irregular shape could not be skipped reproducibly, so I made symmetrical disks of sandstone in a range of diameters. The technique involved grinding a rough stone into a flat slab with parallel surfaces and then grinding the edges to make a perfect disk. I used an ordinary grinding wheel to make the slabs.

"A small hole was bored through the middle of the slabs with a cement drill. A bolt placed through the hole served as a mandrel for locking the flat stone in the chuck of an electric drill. The irregular edges of each slab were then ground into a true circle by holding the spinning stone against the grinding wheel. Finally, I painted the stones white so that they would photograph easily.

"I then applied a pair of black stripes that extended from the hole to the edge on one side. On the other side I painted a single stripe from the hole to the oppo-



Kirston Koths' apparatus for skipping stones site edge [*see top illustration on next page*]. This distinctive pattern of markings made it easier to determine the orientation of the stone in photographs made during its flight. Other apparatus used in the experiments included a microphone, an amplifier, an oscilloscope, a stroboscope, a still camera and a high-speed motion-picture camera.

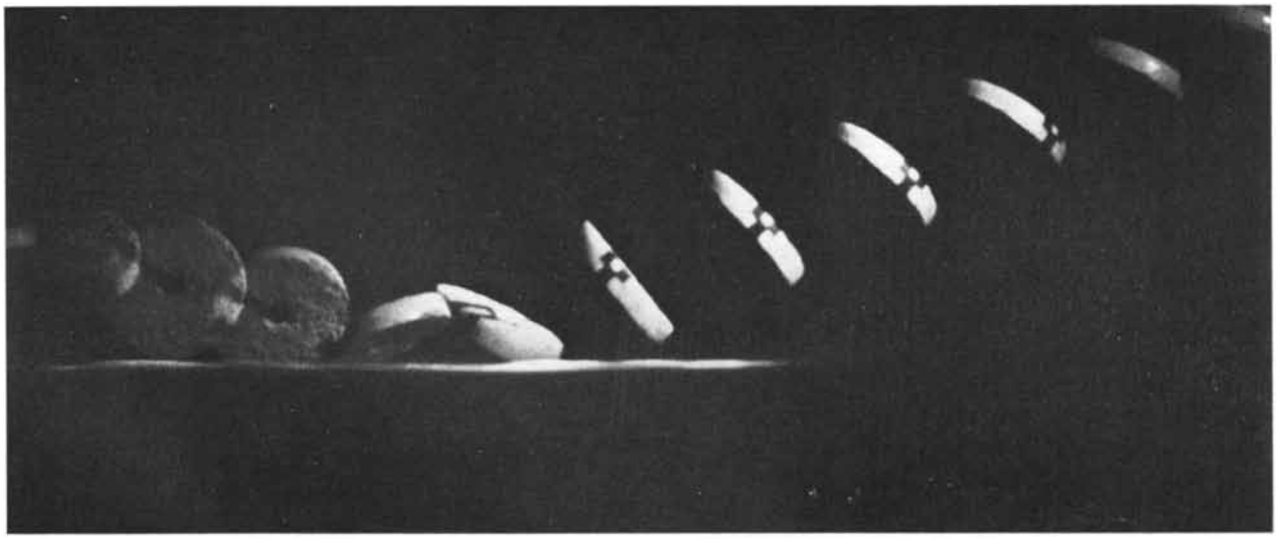
"I was not familiar with the best way to photograph a skipped stone. I did not know whether it would indeed make two closely spaced impacts as Wright had predicted. My first experiment was made to learn something about the velocity so that I could adjust the stroboscope to the optimum flash rate.

"I placed the microphone close to the tabletop and adjusted the oscilloscope to begin a horizontal sweep at the instant the microphone picked up sound above a predetermined volume. The spot of light that appears on the face of the oscilloscope tube was adjusted to sweep from left to right at the rate of five milliseconds per centimeter. The intensity of sounds was indicated by vertical excursions of the spot.

"The stone in skipping on the cloth-covered table definitely made two closely spaced impacts as indicated by the oscilloscope. The recorded pattern [*see middle illustration on next page*] shows that the vertical excursions reach maximum amplitude twice near the beginning of the sweep. The sweep does not start until the sound of the first impact approaches maximum amplitude. For this reason only the final portion of the first impact is displayed. The interval between the two impacts spanned roughly .01 second, indicating that a minimum of 150 to 200 flashes per second would be required to record the path and orientation of the stone between impacts.

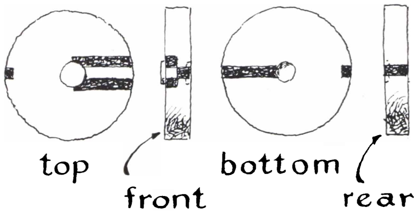
"To make photographs by the repetitive-flash technique the room must be darkened and all background objects should be black. The shutter of the camera is opened. After the scene has been illuminated by a series of flashes the shutter is closed. The film is exposed during each flash and records a picture of the stone's position at that instant.

"The lamp I used emitted flashes that lasted less than half a millionth of a second—about as long as it takes an automobile moving at 60 miles per hour to travel the thickness of its paint. For this



Specially marked stone skipping on the tabletop

Same type of stone skipping on sand



Marking on stone

reason the images of the stone in flight were sharp.

"The stone reflects the light of only a single flash at each of its positions as it passes through the field of the camera. The background, however, reflects the light of all flashes. For this reason light reflected from the background must be kept low to prevent the film from being overexposed if the shutter is kept open for a half-second, the exposure I used.

"Some photographs were made against a background of black velveteen, which reflects only about 1 percent of the light that strikes it. In other experiments I cleared an area of the background about 50 feet in depth. This had the effect of creating a black background because light reflected by 100 flashes from objects at a distance of 50 feet was not sufficient to expose the film significantly.

"The stone was thrown by hand in all experiments. The direction of rotation of the stone was easily determined on the basis of the hand from which it was released. A right-handed throw resulted in clockwise rotation, a left-handed throw in counterclockwise rotation. The distances between hops of the stone were measured from the centers of the marks made in the sand.

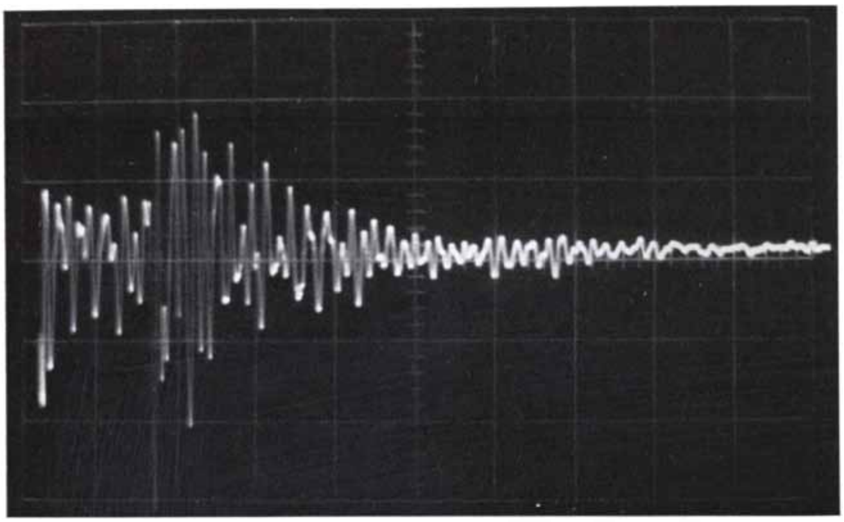
"By averaging the results of scores of experiments I reached the conclusion that the length of the short hop is proportional to the diameter of the stone. As the diameter of the stone increased, the length of the short hop increased. I also observed that the points of impact were alternately displaced sideways, creating a wavy pattern. As viewed from above, a clockwise throw made an initial mark in the sand that indicated a deflection to the right. The second impact was deflected to the left, the third to the right and so on. A counterclockwise throw made a similar alternating pattern, beginning with a deflection to the left.

"The initial attempt to photograph a stone skipped on natural sand failed because the light color of the sand overexposed the film. The sand was therefore colored black with a dye designed for use on cloth. When making the pictures, I turned out the lights and activated the stroboscopic flash. Then I simultaneously threw the stone and opened the shutter, using a cable release.

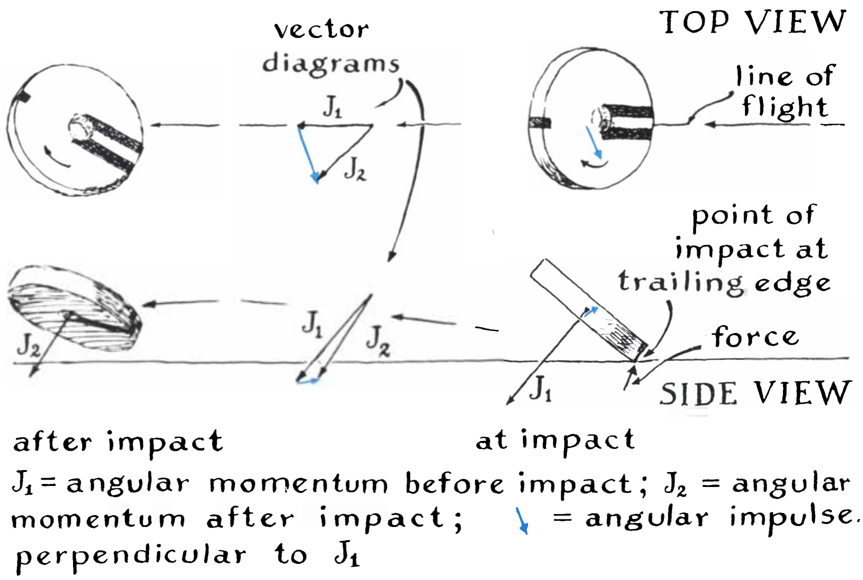
"The behavior of the stone was determined by analyzing the photographs. The center of mass of the stone was marked with ink on each recorded image. Then the centers of mass of the three images immediately before impact were connected by a straight line, with allowance made for the natural parabolic trajectory of the stone. The angle made by this line and the horizontal was measured and recorded as the angle of approach. The angle of departure was similarly determined and recorded. The tilt of the stone—its angle of attitude prior to impact—was determined by measuring the angle of the image that immediately preceded the stone's contact with the sand.

"Normally a stone makes initial contact at the trailing edge and then strikes on the leading edge; a short hop results. The initial impact, which makes the first mark in the sand, exerts a torque that causes the stone to topple forward and strike the sand at the leading edge, where it makes the second mark. Then, depending on the angle of approach, the angle of attitude and the uniformity of the surface, the stone will either continue to topple or will right itself. Following the double impact, the stone makes a long hop.

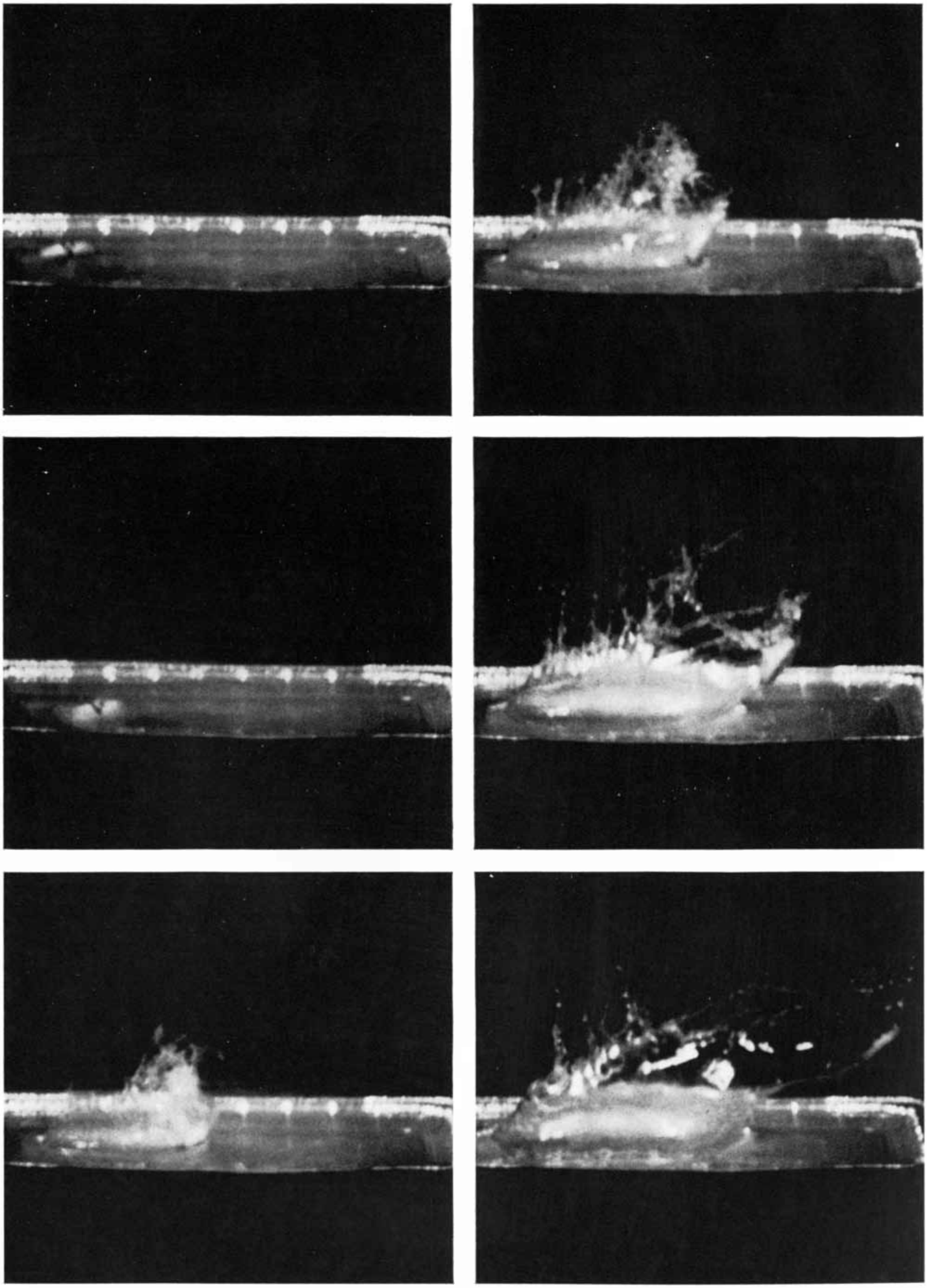
"Stones that make initial contact with the sand at the leading edge behave in essentially the same way if they skip at all; usually a stone that strikes first on its leading edge will dig into the sand and



Oscilloscope trace of stone skipped on tabletop



Force vectors of a stone skipped on sand



Sequence (reading down) *of a stone skipping on water; its motion is to the right*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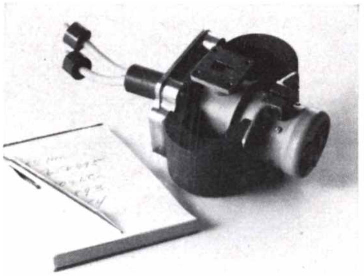

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come to rest. If it skips, the sequence is as follows. The leading edge lifts from the sand. The trailing edge then makes contact at or very close to the point of impact of the leading edge. Only one mark is made in the sand before the long hop.

"The lateral displacement of alternate marks made by a skipping stone in the sand arises from the rotation of the stone about its axis. The spinning edge exerts a sideways force on the sand as it makes impact. The sand in turn deflects the stone to the right or the left depending on the stone's direction of rotation and on which edge hits first, the leading and trailing edges having oppositely directed velocity vectors.

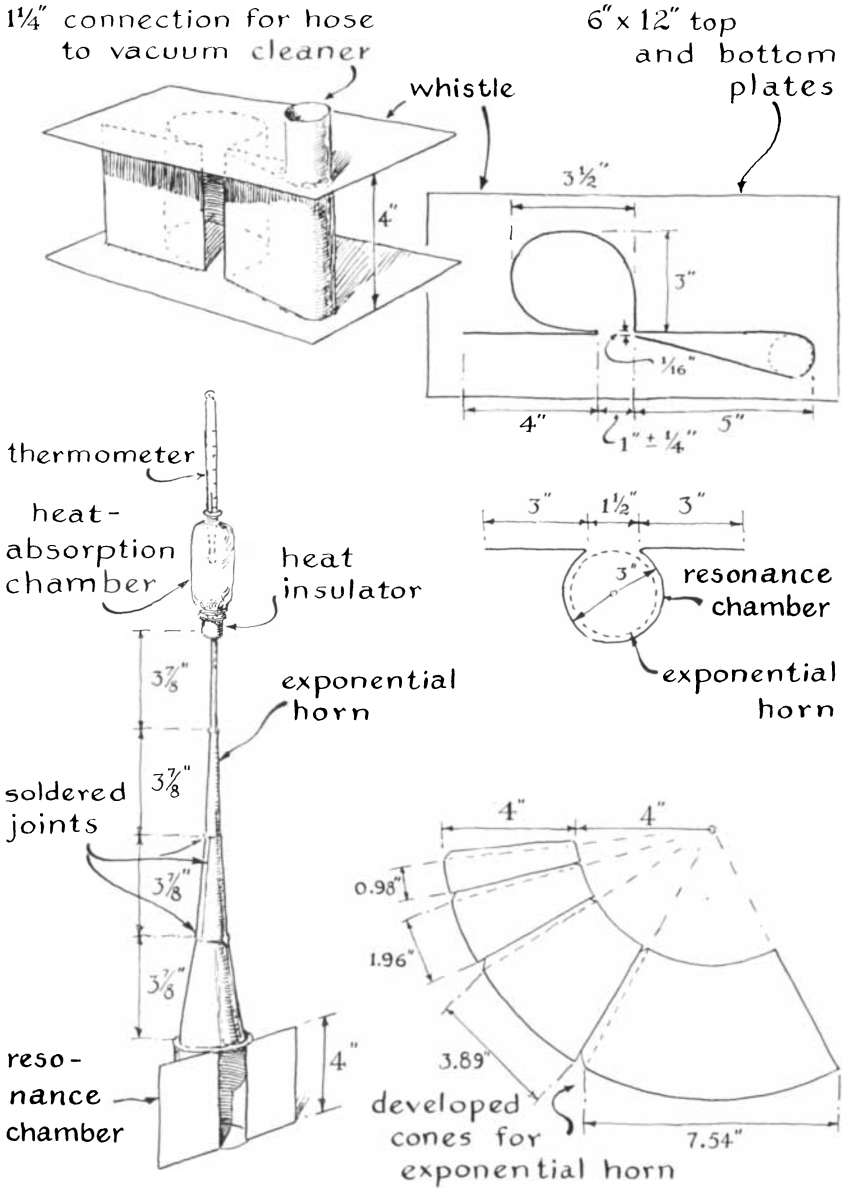
"Still another motion is evident in the photographs. When the tumbling force of the torque that is exerted on the stone by impact with the sand is imposed on the spin imparted by the throw, the stone begins to precess, or wobble, like a spinning top that is pushed from the vertical. In this respect the spinning stone is like a small gyroscope.

"The angular-momentum vector is determined by the direction of rotation, the angular-impulse vector by the edge that makes contact with the sand. Adding the two vectors, it is clear that a stone spinning in the clockwise direction and striking at the trailing edge will precess toward the right. Similarly, a stone that has counterclockwise rotation will precess toward the left. The gyroscopic effect thus produced is not great, however, because of the relatively low angular velocity with which the stone is thrown.

"In many photographs the linear and angular velocities of the stone as well as the angle of approach were almost identical, but the angles of departure varied greatly. The angle of attitude was the only significant variable. Hence I concluded that the angle of departure in the case of stones skipped on sand must be a function of the angle of attitude.

"The repetitive-flash technique did not work well in the case of stones skipped on water. Splashes obscured the details at the moment of impact. I therefore substituted a high-speed motion-picture camera for the stroboscopic flash and filmed the events at 600 frames per second at an aperture of $f/2$. The pictures were taken from the side at a distance of 12 feet and from a point slightly above the horizontal. The analysis was made by printing key frames of the film as still photographs [*see illustration on page 115*].

"The photographs show that a stone skipped on water does not react like one skipped on sand. When a stone is thrown at an angle of about 20 degrees, the trailing edge makes contact first. The stone planes along the surface of the water and then tilts backward to an attitude of approximately 75 degrees. A crest of water builds up in front. The stone now lifts out of the water and makes a long hop. The entire interaction of the stone and the water is quite complex, so that it may be possible to throw a stone of some other shape in some way that would cause it to make a double hop, as Wright suggested. All the stones I threw, however, made single impacts followed by long leaps."



Equipment devised by George R. Stibitz for experiments with sound

Music is often spoken of as though it were a branch of thermodynamics. Louis Armstrong is said to blow the hottest trumpet, and Herb Alpert has the reputation of conducting the coolest brass group. Anyone who wants to put such observations to a literal test can do so by means of techniques that measure music in terms of heat. George R. Stibitz of the Dartmouth Medical School has developed an apparatus that transforms sound into heat and measures the resulting temperature with a thermometer. Stibitz writes:

"It is no startling pronouncement to say that sound is a form of energy or that sound turns into heat when it is absorbed. Those who regard the term 'hot music' as nothing more than a colloquialism, however, might be surprised to watch a thermometer rise above the boiling point of water in response to the absorption of sound by a piece of cloth.

"Any object as large as a thermometer radiates an appreciable quantity of energy, particularly at temperatures above 100 degrees Fahrenheit. To raise its temperature above that level requires a fairly powerful sound. A big loudspeaker could radiate sufficient energy, but I turned to a different source of sound for my apparatus. I designed a powerful whistle, which is shaped like the ones used by traffic policemen but is considerably larger.

"The whistle, which is blown by the exhaust of a vacuum cleaner, was made by bending a strip of sheet metal 26 inches long and four inches wide into the shape of a jet directed across the mouth of a cavity. I then soldered end plates to the sides of the bent strip [*see illustration on opposite page*].

"The whistle radiates sound in all directions, but the loudest sound comes from the opening of the cavity. In order to concentrate the acoustic energy and direct it into an absorbing chamber I constructed a crude horn of the exponential type. It picks up sound waves over an area of 10 square inches and directs them (through an opening of 1/20 square inch) into the absorbing chamber. The whistle and the horn were designed to generate a sound at about 528 cycles per second, one octave above middle *C*. Unfortunately the human ear is very sensitive to that frequency. A lower pitch would have been more comfortable during my experiments but would have required a larger whistle and horn.

"Essentially the horn is analogous to an electrical transformer. It matches the acoustic impedance of the region in the vicinity of the whistle (about one acoustic ohm) to the impedance of the absorption chamber (100 acoustic ohms). The horn is not truly exponential, but it approximates this form by a series of conical sections four inches long with ends that have a ratio of 2 : 1 in diameter. The large end of the horn terminates in a cylindrical resonance chamber about three inches in diameter and four inches long. The chamber contains a rectangular opening 1½ inches wide and four inches long flanked by a pair of flat wings three inches wide. The end plates of the whistle are placed close to the wings of the resonance chamber for coupling the source to the load.

"The absorption chamber was designed not only to transform sound energy into heat energy but also to prevent the loss of heat. The body of the chamber is a cylinder of cardboard (cut from a mailing tube) about 1¾ inches in diameter and three inches long [*see illustration at right*]. The cylinder is coupled to the small end of the exponential horn by a short bushing of wood. The low thermal conductance of the wood keeps heat from flowing rapidly into the metal horn.

"I made the bushing of wood dowel by drilling a 1/4-inch hole through the axis. With a little filing the bushing made a snug fit with the end of the horn. The bushing must be cemented to the horn to make an airtight joint. A remarkable amount of acoustic energy can escape through even a few pinholes at the small end of the horn.

"The absorption material consists of a pad of finely woven cloth. It covers the inner end of the wood bushing. The thickness of the cloth pad must be adjusted by trial and error for maximum performance. I found 15 layers of dress-lining material about right.

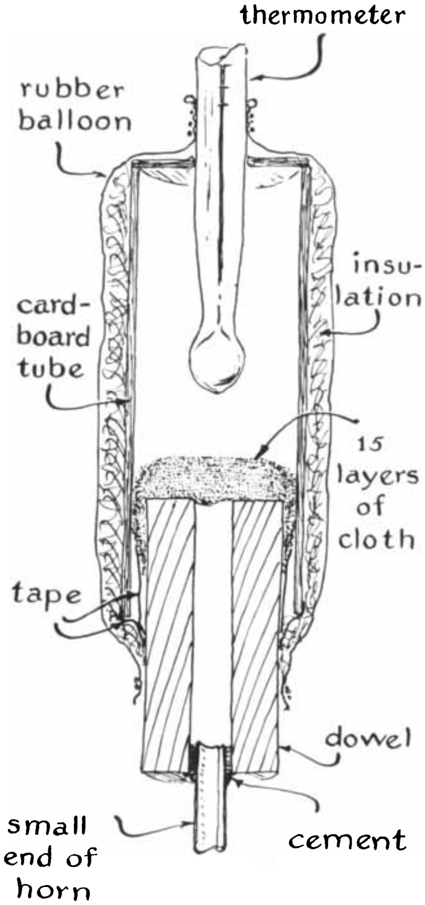
"The cloth pad is held in place by masking tape. The mailing tube must also be cemented or taped to the dowel. In addition the tube must be insulated with a layer of absorbent cotton or glass wool and covered with sheet rubber of the kind used in rubber balloons. The rubber sheet prevents a steady flow of air from the horn and so minimizes the loss of heat by convection.

"A candy thermometer makes a convenient indicator; an oven thermometer will work as well. Insert the thermometer through a hole in the rubber sheet. Then tie the rubber tightly around the thermometer to prevent the escape of air from the chamber.

"When the operating whistle is brought close to the resonance chamber of the horn, the thermometer should rise 40 or 50 degrees F. after a few minutes of warm-up. The results will depend critically on the relative positions of the horn and the whistle. Another important factor is the acoustic resistance of the cloth pad.

"The apparatus can be modified in a number of ways. For example, a wad of absorbent cotton placed in the hole of the bushing makes an efficient converter, but it is difficult to adjust. The acoustic resistance of the wad must come close to matching the impedance of the horn. The resistance changes greatly with comparatively small changes in the density of the cotton. The density of the cotton is determined, of course, by the pressure with which it is pushed into the dowel.

"A more efficient design can be made by constructing the whistle and horn as a unit, but the adjustment of the coupling between the whistle and the resonance chamber then becomes difficult. My most efficient design created a temperature of 250 degrees F. The model described can easily be adjusted to create temperatures of 130 degrees. I have found that a space of 3/4 inch between the opening of the whistle and that of the resonator works well, depending on the pressure created by the vacuum cleaner, the shape of the whistle and the effectiveness of the pad in the absorption chamber.



Details of the absorption chamber

"An interesting experiment consists in measuring the amount of power that is converted from sound to heat. The experiment can be done by inserting a small tube of water in the thermometer hole and measuring its rise in temperature. A rise of one degree centigrade per milliliter of distilled water is equal to one calorie, or 4.2 watt-seconds.

"The power delivered by the stream of air can also be measured. Clear plastic tubing bent into the U shape of a water manometer can be used for measuring the drop in pressure across the mouth of the whistle. The rate of airflow can be estimated with reasonable accuracy by means of a pinwheel made of paper. The power expended by the air is estimated by taking account of the rate of flow and the drop in pressure."

BOOKS

A collection of shorter reviews

SHAMANISM: THE BEGINNINGS OF ART, by Andreas Lommel. McGraw-Hill Book Company ($12). The Tungus people of Siberia gave us the word "shaman." It "designates a certain excited, restless state." The office of shaman is not just Siberian; it is not even restricted to the North American Indians, those wandering Siberians. Shamans are found in nearly every surviving hunting culture, from the Eskimo circumpolar hunters (described so well by Knut Rasmussen reporting their own words a generation ago) to Tierra del Fuego, the Kalahari Desert and particularly to Queensland in Australia (where the author, a distinguished German ethnologist, has himself worked). The shaman is not a medicine man, even though he may heal; he is not the worldly physician and ritualist. He is not a priest either; his work and his words are only secondarily religious. He is a man whose weakness in the world has led him through a passage of severe depressive mental illness, which he overcomes again and again by transforming his own disease into an indispensable game of performance. Working in an intense and exalted trance, using mime, drum, song, dance, painting and sculpture, the shaman transmits to the few dozen or at most the 300 or so persons who form his community a new vision of the deepest images of their mythology. With hunting peoples the myth is always an animal myth; its function is to help dissolve the terrible fears of a small and lonely band in a world that men do not dominate—the fear of universal death through the loss of female fertility, of famine through the disappearance of game, of decimation by strange fevers. The shaman works by the artistic invocation of the spirit of the animal rulers of the spirit world, whose desires he voices. A metaphysics of the soul is implied: in a special place deep inside the body resides the soul of every animal, and indeed of man. The visual art inspired by shamanism most characteristically depicts animals in an "X ray" style. The X-ray style portrays animals showing internal organs such as the heart, the bones and the gut. According to Lommel, such paintings are often executed, at least in Australia, in a dreamlike ecstatic state, less binding than true trance but by no means fully conscious.

It is seductive to think that some of the enigmas of Paleolithic cave art and its placement are related to the abnormal intensity of the artist's state of mind. It is certain, and the evidence lies before one in the color plates and carmine marginal drawings of this handsome book, that the art of the shaman, like his face (we see that here too), has a brooding intensity. Often the art, like the masked and robed dancer, presents images in which man and animal somehow fuse. In the art of medieval China, Japan and Turkey we can often see clear signs of the shaman's influence.

The Australian shaman sat on a snake that flew off with him to the spirit world. Today "the old accounts, which . . . no longer carry their old unquestioned conviction, are becoming credible again through the white man's ability to fly. . . . An attempt was made to persuade me to believe accounts of the killing and resuscitation of a man . . . by telling me . . . about an operation which an aborigine in a hospital had undergone and which several others had apparently watched. The man had lain as though dead. The white doctor had killed him; then he . . . took out his entrails; he washed them, replaced them. . . . After a long time, the dead man came back to life. He could not remember anything. . . ." In northwestern Australia the white doctor generally appears in an airplane.

Shamanism is very old, although it is far from proved to be "the beginnings of art." It is old and it changes, particularly in these peripheral cultures, driven to the ends of the earth and yet receiving a steady dilute infusion over the millenniums from the metropolis; this is seen in the iron ornaments of the Tungus shaman's robes as well as in the airplane of Australia. Lommel nowhere refers to the use of psychedelic drugs, although others have remarked on the relation of such drugs to shamanism. We can recognize in the entire story many details that are still part of our lives, we who no longer hunt but still find ourselves hunted.

The publisher has given us a beautiful book, although at a rather high price; he ought to accept the blame for the absence of an index to this important work.

THE TIMES ATLAS OF THE WORLD: COMPREHENSIVE EDITION, produced by The Times of London in collaboration with John Bartholomew & Son Ltd. Houghton Mifflin Company ($45). ROAD ATLAS: 44TH ANNUAL EDITION. Rand McNally & Company ($1.95). These are proud years for cartographers. Orbiting cameras are viewing our earth on the scale of the map maker for the first time. The photographs we so eagerly scan show no surprises, no new lands, no strange shapes. They look just like the maps so patiently woven out of the skeins of data inched out on the ground. This is the map maker's triumph.

The new *Times Atlas*, weighing 11 pounds and seeming as large and imposing and quite as royally scarlet as one of Her Majesty's pillar-boxes, is a welcome to the space age from the classical map maker. The book mainly presents 120 attractive two-page plates, depicting the entire world and its political boundaries, with tinted contours to show altitudes and ocean depths. The volume is easier to use than its huge five-volume predecessor, at about a third of the price, and its maps are basically the same maps and the same size as in that earlier edition. The maps are artfully bound in one volume, so well made that it is agreeable to use on a tabletop in spite of its size. The binding is so well done that one can follow the printed legends deep into the crevasse of the center fold and still read them tolerably well. An imaginative quick index is given on the endpapers, where numbered rectangles mark out on a map of the world the coverage of each numbered page, without words. Brilliant! There is also a huge gazetteer-index of 200,000 listings. Everything works well (barring a page of dubious text on the surface of the moon), and the execution is good at every point, in a suitable if somewhat old-fashioned style. Even the high price is fair for all that information on such excellent paper.

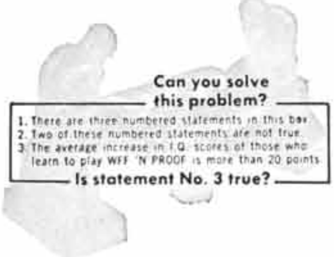
Utopia, however, is still not to be found in any atlas. Users will find here political maps in rich detail, but only for the great range near Mount Everest, and for generalized maps of the entire world scale, is there any version of that graphic shaded relief which modern cartography has come increasingly to use—a far more immediate physical guide than even the best tinted contours. The conservatism of map makers has put this atlas behind the best grade of atlases put out by several American publishers, who for about half this price generally offer detailed physical coverage, state by state of the U.S. at least, in some form of shaded relief. The *Times Atlas* has specialized in the political map, and it handsomely gives a good deal more than twice the usual yield of worldwide place names and political detail, at the cost of some generality of purpose. The atlas is full but not really comprehensive. For the U.S. only the strip from Washington to Boston is presented at the one-to-a-million scale that dense population and detailed interest demand. Tiny Iceland, however, is mapped on one large double page, and the nations of western Europe, the U.S.S.R. and the Commonwealth countries are particularly well displayed. London, Paris and Brussels earn fine maps; New York has an adequate one; the other U.S. cities are sketchily treated. Watts cannot be found, nor the accelerator site in Weston, Ill., nor indeed any U.S. county by name.

An American reader who wants this superior world political atlas cannot really manage without any reference to the counties or to many city districts of the U.S. For him there is a bargain remedy: the *Road Atlas* presents a wealth of information—places, roads, parks—for the U.S. and some of its neighbors (with almost no physical data), detailed maps of most cities, even of moderate size, and it names and maps the boundaries of all 3,000 U.S. counties. It is an admirable complement to the big red book.

The Constructive Uses of Nuclear Explosives, by Edward Teller, Wilson K. Talley, Gary H. Higgins and Gerald W. Johnson. McGraw-Hill Book Company ($12.75). These four engineer-scientists of the Lawrence Radiation Laboratory at Livermore here present a useful account, on the level of a text for advanced engineering undergraduates, of nuclear explosions and their effects from the point of view of using the effects as engineering tools, for surface construction of harbors and canals, for building underground storage vessels or for mineral extraction. Most of the material is obtained from the considerable body of theoretical and experimental work done under Project Plowshare, first conceived under the stress of the 1956 Suez crisis, they say, as a quick way to replace the blocked canal. Plowshare has often seemed to have a larger component of politics than of economics in it; the claimed potential of the peacetime developments, so far without a single success to their credit (up to the Gasbuggy shot in May), has been used here and abroad as an argument first against the partial ban of nuclear testing and then against the proposals for a treaty on nonproliferation. This book lies almost wholly at the engineering level, although there are those who might more conservatively estimate the radiation hazards.

Suppose you drill a shaft a yard wide and 2,500 feet deep into hard rock. Lower the 10-foot canister of the 100-kiloton explosive, weighing five tons, carefully into the hole. The Atomic Energy Commission estimates it will cost you about half a million dollars for the explosive. Plug the hole carefully with 50 feet of concrete and a pile of whatever you have handy. Fire! Deep in the earth a sphere of vaporized rock will form in a fraction of a second, its walls lined with molten rock. It will reach in that time a diameter of 300 feet. The molten rock will flow slowly down the walls and drip from the roof. After a brief period the unsupported roof will collapse, depositing its rubble to fill the bottom of an irregular chimney. Before these effects were observed it was thought that the molten rock—particularly if the shot were set off in salt—might simply seal the walls, form a molten pool at the base and sit there holding its heat. Then a new drill hole could bring in water to flash into steam, and thermonuclear energy would be at hand. It is not that easy. In 200 underground shots only one tight sphere remains. One even puffed radioactive gases in spite of the plugged drill hole.

There is a study of a new Panama canal to be dug by nuclear shots, one of which is to be 35 megatons! The savings over regular earth-moving techniques are said to be large, but neither development costs nor legal ones are considered. There is a curiously incomplete chapter on bomb physics, which handles Liouville's theorem, Thomas-Fermi equations of state and a good deal of unconventional hydrodynamics (it is not true that there is no photon-photon interac-



tion at all, as stated) but barely lists the possible reactions of a thermonuclear explosion. Reading these chapters is a bit like seeing a badly cut film. But all in all there is no more up-to-date and complete text on nuclear explosions, their radioactivity and their general effects, particularly at the surface and underground. Air blast and fireball are of course better treated in the official AEC volume on effects.

The photographs of these underground shots are remarkable. Most awesome is the dome that bulges upward at the surface when the explosive is set off half a mile below.

Wood as Raw Material: Source, Structure, Chemical Composition, Growth, Degradation and Identification, by George Tsoumis. Pergamon Press Inc. ($10). One important consequence of the sun-driven evolution of the earth's biosphere is the production of hundreds of millions of large tapering cylinders about 30 feet long and 20 inches or so in diameter, with wide variations, that stud by the hundreds of millions the wetter portions of all lands between the Arctic Circle and the Antarctic. These cylinders are in fact aggregates of small tubes, a millimeter up to several millimeters long, and only a hundredth as large in diameter. The tube walls consist of crystalline arrays of glucose polymer, with 10,000 glucose links stretching a few microns, woven in many-ply layers. Each of these fibrous tubes is as strong as steel to a pull along its axis. The great bundle of tubes is glued together (to strengthen it against tension, bending and compression alike) by an almost equal weight of a rather soluble adhesive. Some of the adhesive is a related polymer of other sugars, chains of which are partly built into the tube walls, and some of it is a peculiar amorphous mix of aromatic hydrocarbons found nowhere else in nature. Often the bundle of tubes has a small content of organic pigments, preservatives and fragrant volatiles.

These bundles are of course the stems of forest trees—what we call wood. Most of the crop is still taken from the wilderness, but farming is well under way, particularly in Europe, where even nonpropagating hybrid trees, like our hybrid corn, are sown. Depending on the species of tree (there are a couple of hundred in commercial use in Europe and America, and 10 times more in the Tropics), the wood may be used, after drying and cutting, as a natural composite material for structure and decoration or as mere dirty bundles of cellulose fiber to be pulped for their 50 percent of cellulose content—our paper and our film.

In every stem is a history of growth, of branching, of seasons, of slow change of form and vigor, of the pressures of wind, of the inborn errors of morphology and biochemistry. It is recorded there, visible to the eye, the microscope, the electron micrograph, the analyst. In this not very technical but knowing book, half text, half reference work, a broad and clear view is taken ranging over the long list of topics in the subtitle. The photographs are fascinating, and each chapter has a long list of references to the primary technical sources for this admirable survey. Professor Tsoumis teaches foresters at the Aristotelian University in Thessaloniki.

Language and Symbolic Systems, by Yuen Ren Chao. Cambridge University Press ($1.95). One of the growing points of the tree of knowledge, watered by a storm of technological innovations and producing intoxicating philosophical secretions, is the science of symbols. There have been a good many books for the general reader on the matter, coming from reflective physicists, experimental psychologists and an occasional mathematician. The linguists proper, seized with forming their science anew and being hotly polemical, have not recently been producing books apart from their exacting monographs. Here is a witty, personal, warm and helpful little book that presents, as the disarming preface states, "views on language different enough to justify another book."

No school is espoused, no theory strongly urged. Professor Chao, a veteran Berkeley scholar, begins with a low-key survey of the general issues of linguistics, moves to present briefly and clearly the elements of the modern point of view, with its nice distinctions of phoneme and morpheme, of type and token. Grammar too, with its modern mathematical forms, its logical nesting and remappings, is gracefully described. The author is a thoughtful ex-physicist turned descriptive linguist, so that he fills his general forms with engaging examples and asides. In fact, he devotes most of his book to a wider area, telling about meaning and about acoustic phonetics. (He reproduces the sound spectrograms for "Pam you ungelfpangg thob I fay?" and its more conventional counterpart: "Can you understand what I say?") He particularly takes up the modern electronic systems that put the spoken and written language through all sorts of hoops of energy mode, time and frequency-space. He is a sympathetic and practical adviser to those who would be bilingual; above all he is a learned scholar in both Chinese and English, which gives an authority that few enjoy to his remarks on the diversity of languages. Where else can you find a Chinese paragraph, consisting solely of 36 repetitions of the single syllable *hsi* (using four tones, to be sure), that he assures us a reader of classical Chinese can make out to be a somewhat improbable story about a Mr. Hsi who regularly took his pet rhinoceros to West Creek for an evening bath and romp? The whole brief book is like a cheerful and informed conversation with a man of rigorous mind, tolerance, wit and a cosmopolitan treasury of knowledge.

LIFE OF JOHN WILLIAM STRUTT, THIRD BARON RAYLEIGH, O.M., F.R.S., by Robert John Strutt, Fourth Baron Rayleigh, F.R.S. The University of Wisconsin Press ($10). Here is a modernized and "augmented" edition of the semipopular biography of the last prodigious amateur in physics. Modest and quiet, but a fearfully complacent Tory, the third Baron Rayleigh wrought six rich volumes of papers over the widest range of both theory and experiment. All the physics is classical, in both meanings of that word. Much of the experimental work was done in the laboratory he maintained at his old country house, where he also had a successful dairy farm. His laboratory was productive for decades without the benefit of installed electric power; finally Lord Rayleigh coupled a borrowed alternator to the gas engine that normally powered his cream separator. With this new device he first isolated argon, using the power for sparking his tubes as a slow but effective nitrogen "getter." Most of the ingenious mathematical approximation techniques that still are the bread and butter of theoretical physics are his work, or at least were first made clear and useful in his hands. He founded and brought to maturity almost the whole of scattering theory; he applied it to the blue of the sky, to the diffraction grating, even to the acoustic pattern of the head of a listener. He computed intricate results all his life, rarely using so much as a slide rule. Although he had worked personally with Lord Kelvin and James Clerk Maxwell, he long outlived them: he died in 1919. Classical physics was his teacup, yet as an old man he once told his son (the author): "I saw some of these difficulties myself as soon as anyone, but I doubt if I should have had the enterprise to go in for a quantum theory."

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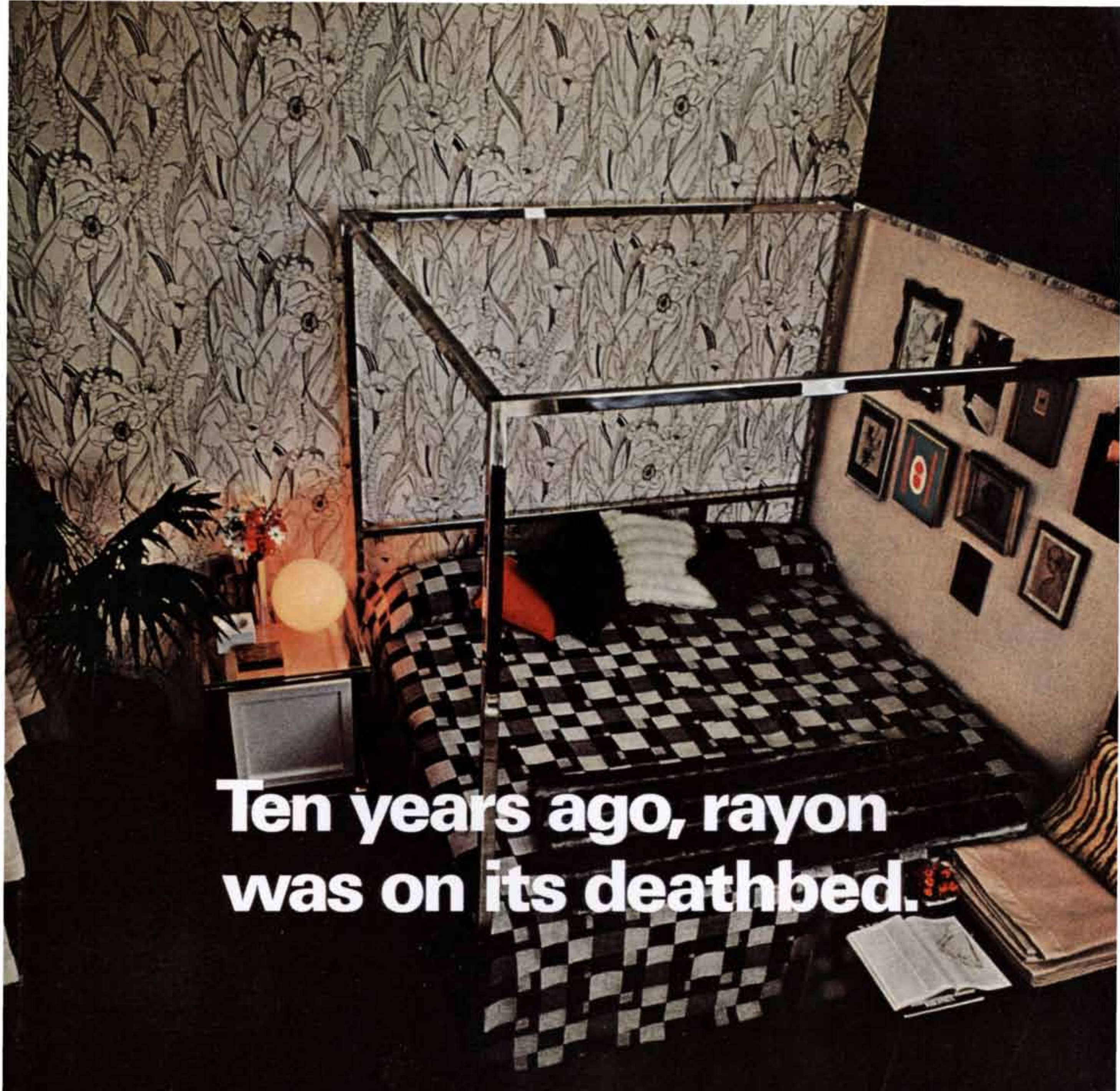

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