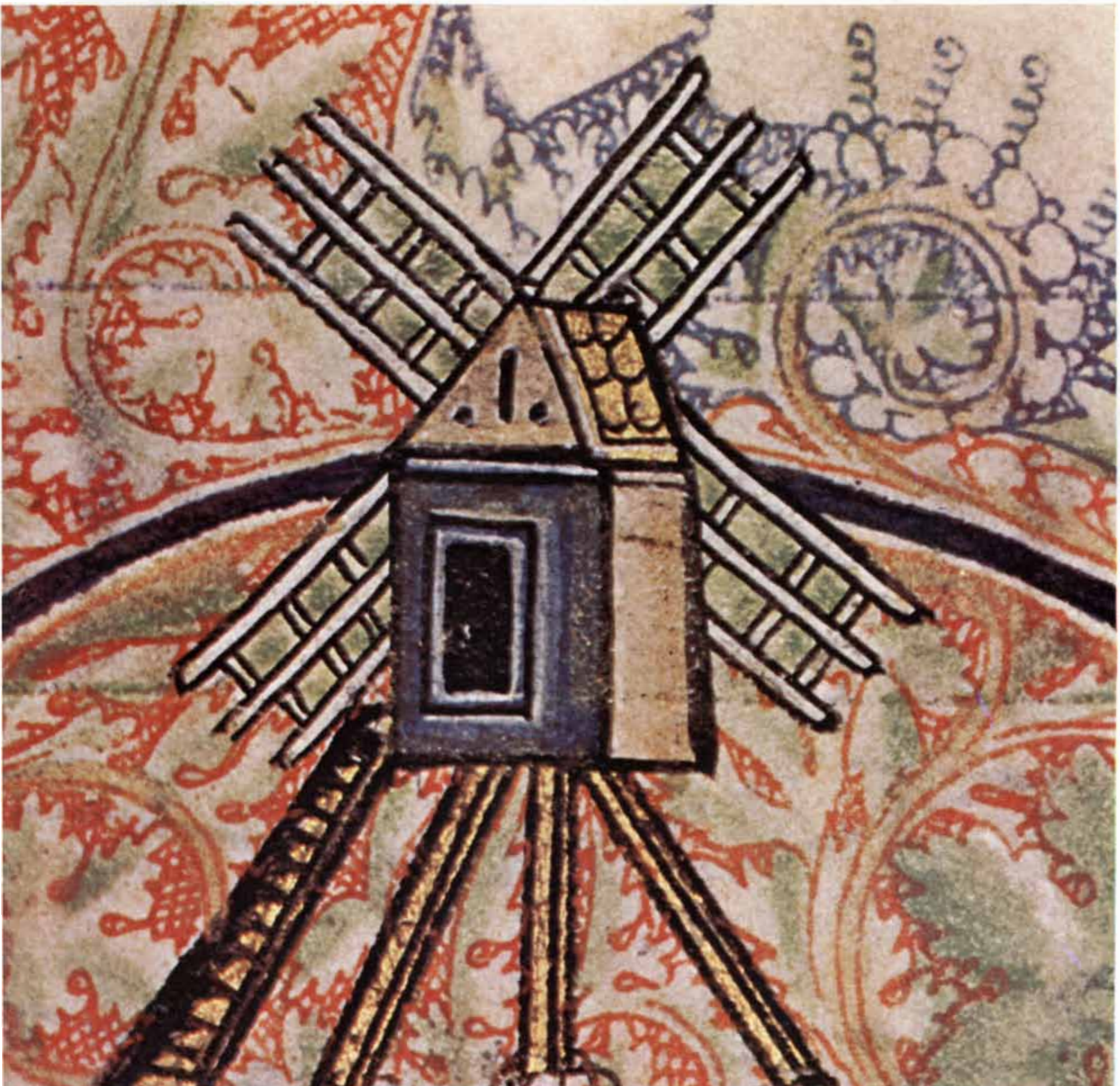
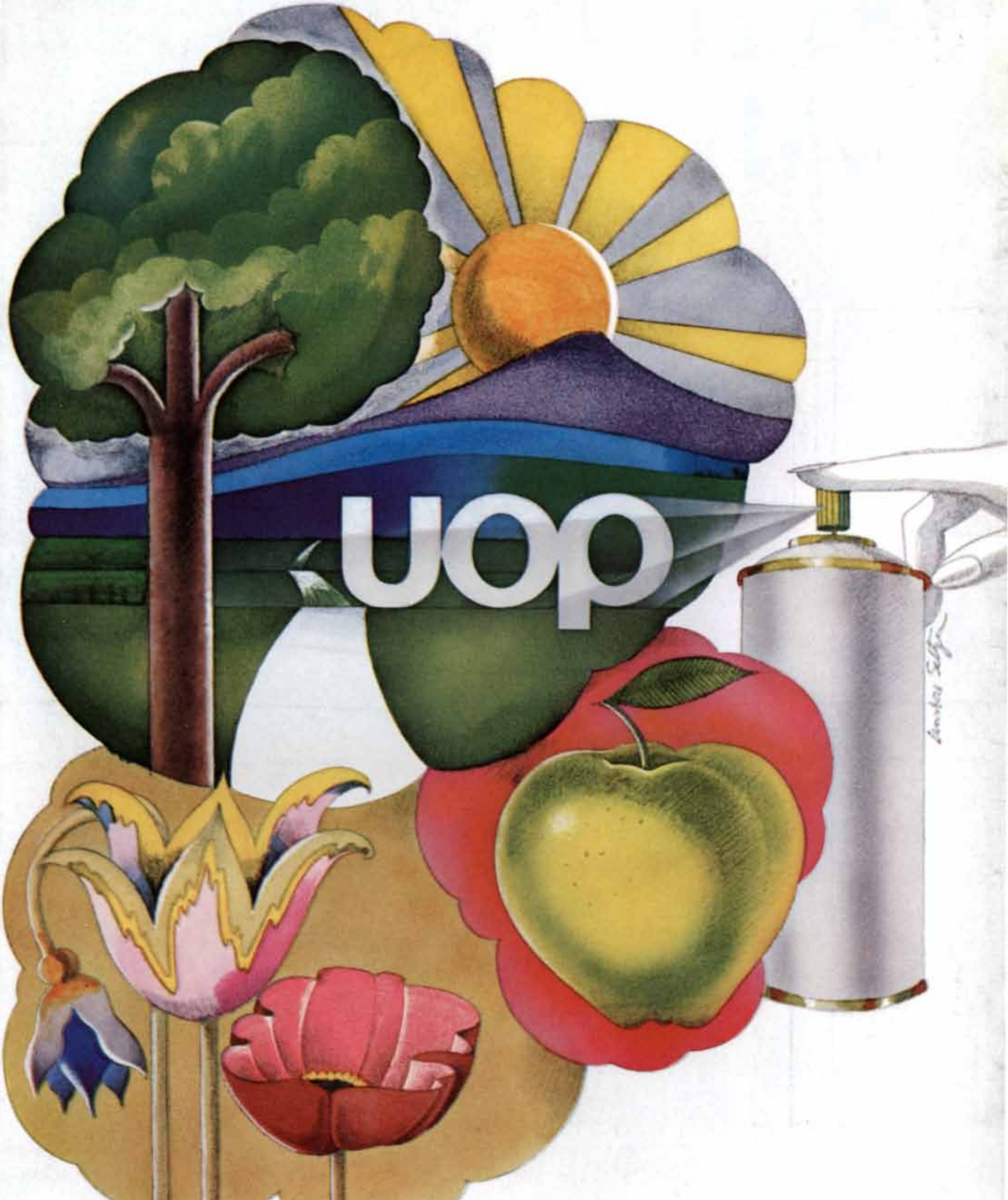
SCIENTIFIC AMERICAN



MEDIEVAL WINDMILL

ONE DOLLAR

August 1970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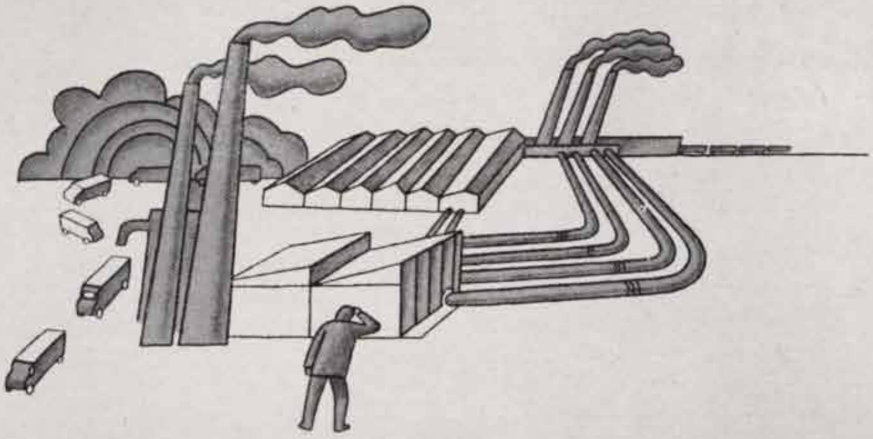

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THE COVER

The illustration on the cover is the oldest known picture of a windmill. It appears in an English manuscript produced in about A.D. 1290. This was perhaps a century after the windmill had been invented in Europe, independent of its earlier invention in the Middle East (see "Medieval Uses of Air," page 92). The picture shows a "post mill," so named because the entire millhouse was rotated on a post in order to present its vanes to the wind. Below the millhouse is the post and its two braces; at the left is the ladder that gave access to the millhouse. The illustration is a detail from the decorative illumination surrounding the letter "E"; the dark curve behind the millhouse is the top part of the letter. The manuscript, known as the Windmill Psalter, is in the Pierpont Morgan Library in New York.

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Cover photograph courtesy of the Pierpont Morgan Library

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LETTERS

Sirs:

The article "The Calefaction of a River" [Scientific American, May] has given rise to some comment in ecological circles out here, especially those people interested in the fisheries, as I am. As a writer I fail to see the point of inventing a monstrous word, "calefaction," as a euphemism for pollution. A rose by any other name, etc.

The entire drift of the article, although written with scientific caution, is apparently that the warming of a river such as the once-proud Connecticut is not harmful, and in fact may be beneficial to aquatic life. However, the author does not tell the reader that the Connecticut originally was one of the great salmon rivers of New England, and one of the best habitats for *Salmo salar* in the world. It was then a cold-water river, and I am certain that nuclear plants will do little good for those who, as you may know, are trying to reacclimatize this species in the river. Shad may thrive in the temperatures created by the nuclear plant but salmon will not.

Perhaps we are reading too much into the article, but it seems to suggest the influence of the Atomic Energy Commission, which is disseminating a lot of propaganda about the nuclearization of our rivers. Incidentally, the word "nuclearization" would have been the most suitable for the title of Merriman's article....

The voters of Eugene, Ore., just voted to postpone construction of a nuclear power plant that its water board, under an arrangement with the private utilities of this region, had planned. In fact, the negative vote, for a four-year moratorium, came less than a year after the voters had approved the plant. The disenchantment with nuclear power is fast spreading around the country.

Anthony Netboy

Office of Programing
Continuing Education
A Division of the Oregon State
System of Higher Education
Portland, Ore.

Sirs:

Thank you for the opportunity to reply to Mr. Netboy, author of the widely acclaimed *The Atlantic Salmon: A Vanishing Species?*

Netboy speaks of my "inventing a monstrous word, 'calefaction.'" The shorter *Oxford English Dictionary* dates the word from 1547, from the Latin *calere* and *facere*, "making warm, heating." It implies neither thermal pollution nor thermal enrichment, both of which are abhorrent to me since each smacks of preconceived bias. Netboy suggests "nuclearization" for my title. That *is* an invented word, misleading because (1) Connecticut Yankee is the *sole* nuclear power plant now operative on the Connecticut River (its warm-water effluent being detectable only over a five-to-six-mile stretch and to a maximum depth of 12 feet), and (2) because it implies nuclear wastes ("irradiation of the Connecticut") when actually the radioactivity levels were lower in 1969 than in 1966 before the plant was operative and no reactor-produced radionuclides have been detected.

Netboy refers to the Connecticut as a former habitat for salmon in superlative terms. His sweeping statements are of as dubious validity as the last sentence in his letter. Nor did we indicate that "shad may thrive *in* [italics mine] the temperatures created by the nuclear plant"; we wrote, "They either pass through or under the plume without apparent difficulty or significant hesitation." So, in my opinion, would salmon, whose extirpation in the Connecticut in the 19th century was the result of old-fashioned damming.

Netboy's insinuation that our work has been influenced by the Atomic Energy Commission clearly impugns the entire Connecticut River Study staff as well as its Advisory Committee. If Netboy had bothered to look at our procedural outline (January, 1965) and the 10 subsequent semiannual reports to the Water Resources Commission, he might be interested to see the names of those toward whom he has directed this affront; he might even admit to the integrity, scope and quality of the study, to say nothing of considering the propriety of apology.

Since Netboy is also engaged in higher education, I venture one final thought. I believe that if there is any single thing our young need to be taught in these confusing times, it is to think, see, listen, read and write objectively and dispassionately so that they may come to reasoned conclusions and act accordingly. The important things are facts, not fanciful assumptions. Netboy preaches objectivity and presents a glaring example of how not to practice it.

Daniel Merriman

Department of Biology
Yale University
New Haven, Conn.

Sirs:

The description of the cover picture of the June issue of *Scientific American* is partly in error. The area represented by the displayed surface covers an area of 20 square miles. The height of the surface does in fact represent magnetic-field strengths in a range of 800 gammas. Color represents gravity readings over the same area. The color transition from green through yellow to red indicates a linear change in gravity readings through 50 milligals. From the color and height of the surface a visual correlation between the two variables can be made. The goal in producing the image of the surface was to show that color graphics using a raster display can be used effectively to represent complex physical relationships that are difficult to interpret by any other means.

John E. Warnock

Computime Canada Ltd.
Vancouver, B.C.

Scientific American, August, 1970; Vol. 223, No. 2. Published monthly by Scientific American, Inc., 415 Madison Avenue, New York, N.Y. 10017; Gerard Piel, president; Dennis Flanagan, vice-president; Donald H. Miller, Jr., vice-president and treasurer.

Editorial correspondence should be addressed to The Editors, Scientific American, 415 Madison Avenue, New York, N.Y. 10017. Manuscripts are submitted at the author's risk and will not be returned unless accompanied by postage.

Advertising correspondence should be addressed to Allan Wittman, Advertising Manager, Scientific American, 415 Madison Avenue, New York, N.Y. 10017.

Offprint correspondence and orders should be addressed to W. H. Freeman and Company, 660 Market Street, San Francisco, Calif. 94104. For each offprint ordered please enclose 20 cents.

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NAME

NEW ADDRESS

OLD ADDRESS

Some things are changing for the better.

Math comes alive for grade school students.

And they're learning it faster than ever before, according to Mr. William Rybensky, program director for computer-assisted instruction (CAI) at Ravenswood City School District, East Palo Alto, California. In his district, students are averaging 15 months of math progress in just 7 months. And at Willow School (where 400 children now regularly use the HP time-share system) some have finished 1½ years of math in less than three months!

And students really like working with our computer, because they receive immediate recognition for correct answers and avoid the embarrassment of making a mistake in front of the whole class. Teachers also appreciate the system. It gives them up-to-the-minute progress reports on every student and eliminates the need for checking answers. So the teacher has more time to coach slow learners and deal with the "why" questions.

For about 25 cents per student per day, any school district can enjoy the benefits of a Hewlett-Packard system, complete with software based on the Stanford Math Drill and Practice curriculum for grades 1 through 6. This $150,000 system is ready for delivery now, completely field-proven and fully supported.

If you'd like to find out how CAI from Hewlett-Packard can help your school district, just drop us a line.

New ways to bypass the big computer.

Enthusiasm for our 9100 Computing Calculator's capabilities has led to a most rewarding exchange of ideas with its users. A typical letter from a California university professor states in part:

"I do not normally write letters of appreciation to manufacturers of products I use, but my joy in ownership of one of your new 9100A calculators impels me to write you my congratulations and praise for a unique product. The design of this machine seems perfectly matched to the needs of a scientist who is continually confronted with minor problems requiring either the use of tables or the fairly laborious construction of a computer program. All too many pertinent problems are ignored because of the work involved.

"We have our own CCI terminal to our (big computer) which is a blessing for big problems, but a headache for little ones. We have repeatedly found mistakes in our Fortran and PL-1 programs by spot-checking the routines with our 9100A.

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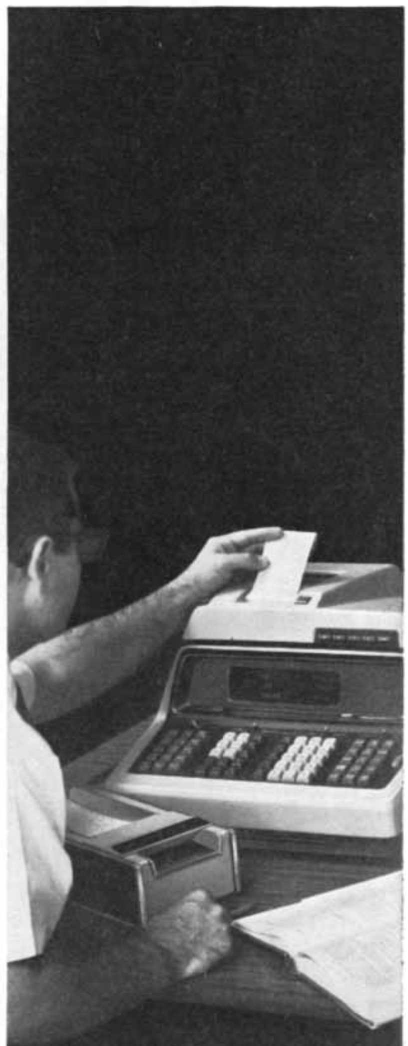
Users like this have helped us compile libraries of programs for our calculator system. The newest of these relates to applied statistics, consists of over 100 programs, and covers the following: General Statistics; Distribution Functions; Test Statistics; Curve Fitting; Harmonic Analysis; Sampling Theory; Analysis of Variance Operations;



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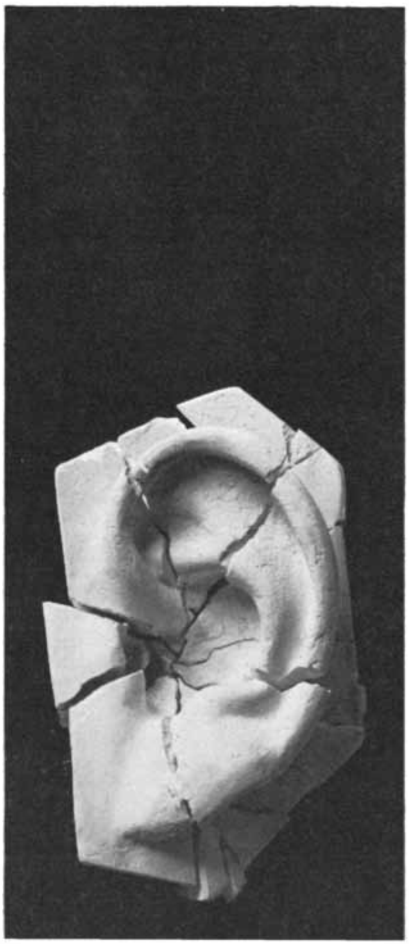
This series of programs for your magnetic cards gives you instant access to the calculators so you can spend all your time on creative data interpretation rather than computation. We call it the HP STAT-PAC. Used with the HP 9100 Calculator System, it can help free you from the laborious reduction of statistics and endless computations. Write us if you'd like more information.

Help for companies with noise problems.

Occupational noise exposure and its potential solutions are currently undergoing extensive investigation by government, industrial, legal and medical experts. Last year's enactment of the Walsh-Healey Act really put teeth in the demands for better industrial noise environment, especially with any firm having Federal contracts of $10,000 or more per year.

If you're one of the people looking for an inexpensive way to measure industrial noise, a new Sound Level Recorder we developed can help you. It's a simple push-button instrument that accurately measures and records all the noise exposure levels and peak sounds covered by the Walsh-Healey Act. If you need certified documents of performance, we have a Sound Level Calibrator that goes with it.

The Recorder costs $2,200, the Calibrator $285. We'll be happy to send you details on both instruments, plus information on how you can use them to meet Walsh-Healey requirements.



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When caring for cardiac patients, how can a nurse be sure she will recognize a life-threatening arrhythmia? Or effectively defibrillate in the few vital minutes available? Or simply make good electrode connections to assure continuous, accurate monitoring information?

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This is another example of how Hewlett-Packard technology is helping to change things for the better. More detailed information on any of the above, or any other HP instrument is available by writing to: Hewlett-Packard, 1506 Page Mill Road, Palo Alto, California 94304; Europe: 1217 Meyrin-Geneva, Switzerland.

50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

AUGUST, 1920: "The America's Cup races of 1920 will go on record as the keenest in the history of these contests. Perhaps this statement would be nearer to the truth if the American defender *Resolute* and the British challenger *Shamrock IV* were being sailed boat for boat. The races had not proceeded very far before yachting men were convinced that *Shamrock's* chances of winning the cup, subject to the burden of more than seven minutes' handicap, were very slight. The final and decisive race, held July 27th, was won by *Resolute* in a light and variable breeze. The *Resolute* finished with an actual lead of 13 minutes five seconds and a total lead, including time allowance, of 19 minutes 45 seconds. Thus was concluded the most closely contested series of races ever held on the Sandy Hook course. Sir Thomas Lipton, with the first two races in a 'best of five' series to his credit, came nearer to winning the cup than any of his predecessors. Only once in the past 69 years has the challenger taken a race. That happened in 1871, when the defending yacht *Columbia* was disabled and the race went to *Livonia*."

"In a note on its investigations of the cathode-ray oscilloscope the Bureau of Standards points out the unique value of this instrument as a means of studying the excessively rapid alternations and fluctuations of the electric currents used in radiotelegraphy. The Bureau states that this form of oscillograph can now be designed and constructed with a considerable degree of certainty to suit a variety of different operating requirements. As an implement of research, permitting visual observation of phenomena previously unseen and furnishing data for new ideas and theories, the cathode-ray oscilloscope performs a service that can be achieved by no other device."

"The growing and active interest in the serious discussion of the necessity of adopting the metric system in the United States has been reflected recently in the correspondence columns of SCIENTIFIC AMERICAN. This magazine for many years has believed that the adoption of the metric system, logical in its development and international in its application, would accomplish as much for manufacturing and other industries, commerce and the ordinary transactions of life in the United States as it has done in continental Europe and in purely scientific work, where its use is now universal."

SCIENTIFIC AMERICAN

AUGUST, 1870: "He would be indeed a bold prophet who would venture to predict the duration or the final result of the war that has broken out in Europe. Should the conflict be confined entirely to Prussia and France, the respective forces would appear to be nearly equal. The greater number of soldiers which Prussia can throw into the field is counterbalanced by the power of the French navy. Both sides are provided with modern field artillery and with powerful batteries of siege guns. The Prussians have Krupp's breech-loading steel rifles, the merits of which are considered questionable by some but which it is thought by many will prove very effective when properly worked. The amount of breech-loading artillery possessed by the French seems to have been purposely concealed by that government. The mitrailleuse, to perfect which large sums are reported to have been expended, has yet to prove its superiority to the Gatling gun, which has also been adopted by the French government. It is also said that the Gatling guns have been sent to Prussia. But the two weapons which will do the most in deciding the result are the Prussian needle gun and the chassepot needle gun, which are constructed on the same principle in almost every respect. It will be seen that these arms must be nearly equal in destructive power, and that when opposed to each other terrible carnage must inevitably result. That this carnage can now be averted by the intervention of other powers seems hopeless, and it is probable that some of the bloodiest battles ever recorded on the face of the earth will sadden the annals of the year 1870."

"The French Emperor has commanded the prime minister to make a detailed report upon strikes in general, and particularly upon the recent strikes in France. The war recently inaugurated will probably defer this report, which will undoubtedly be an important document. The Emperor has asked his Council of Ministers if it would not be possible to avoid such strikes in future by the creation of associations, based on the model of the English associations, between the employers and workmen. In the present state of affairs not only do the workmen in a single shop understand each other but also the relations between the trade societies are developing in all countries. The society known in France as the Internationale represents the interests of all societies of workmen in Europe and America. The Parisian sections of this vast association have just published the constitution which establishes between them a solid and permanent confederation. More than 1,200 members were present at the recent general convention."

"That great authority, Professor Huxley, has lately been discussing what he calls 'protoplasm,' or 'the physical basis of life.' He seeks for that community of faculty which exists between the mossy rock-encrusting lichen and the painter or botanist who studies it; between 'the flower which a girl wears in her hair and the blood which courses through her youthful veins.' Mr. Huxley finds it in the protoplasm, the structural unit of the body, the corpuscle, the spheroidal nucleus, which in their multiples make up the body or the plant. However, Professor Huxley has not proved, and it is impossible for him to prove, that these protoplasms may not have essential points of difference. The facts of life cannot be interpreted by the known laws of chemistry and physics. Physiologists cannot yet tell us how it is that 'of four cells absolutely identical in organic structure and composition, one will grow into Socrates, another into a toadstool, one into a cockchafer, another into a whale.' "

"Dr. A. Cabe of Lyons, France, writes that he had in his practice a very obstinate case of constipation in a female subject 80 years of age, who for 60 years had suffered in consequence of a severe attack of dysentery encountered in her youth. The patient having had no passage for 40 days, the doctor tried to induce a contraction of the intestines by the application of electricity. He inserted the negative pole of a Gaiffe battery into the rectum and applied the positive to the navel, and in the course of two minutes the results were completely satisfactory."

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DIVISION OF SCM CORPORATION

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THE AUTHORS

JOHN A. WOOD ("The Lunar Soil") is a member of the staff of the Smithsonian Institution Astrophysical Observatory in Cambridge, Mass. Born in Virginia, he received a B.S. in geology from the Virginia Polytechnic Institute in 1954 and a Ph.D., also in geology, from the Massachusetts Institute of Technology in 1958. He comments: "For several years now I have been calling my research 'extraterrestrial petrology,' that is, rocks from space and what they can tell us about the origin and evolution of other bodies in the solar system. For many years our only source of rocks from space was meteorites, but now obviously we have the lunar samples as well. I have been totally committed to lunar studies since the *Apollo 11* samples were distributed last September. Someday I shall return to meteorite studies; in some ways meteorites are more fundamental to our understanding of the solar system than the lunar material is."

PETER H. ROSE and ANDREW B. WITTKOWER ("Tandem Van de Graaff Accelerators") are respectively president and executive assistant to the president of the Ion Physics Corporation. Rose is also chief scientist of the High Voltage Engineering Corporation. Rose received a B.Sc. in physics from King's College in London in 1945. After two years of research on early jet engines at the National Gas Turbine Establishment he joined Leicester University College, from which he went to the Massachusetts Institute of Technology as a research associate. He returned to England to teach at the University of Birmingham for three years before joining High Voltage Engineering in 1956. He received a Ph.D. from the University of London for his work on electron nuclear scattering using the Van de Graaff accelerator he had built at Leicester in 1955. Wittkower did his undergraduate work in physics and mathematics at McGill University (B.Sc., 1955) and then went to the Cavendish Laboratory of the University of Cambridge (M.Sc., 1959). He worked at High Voltage Engineering from 1959 until earlier this year, with time out to get his Ph.D. at University College London in 1967.

GERALD M. EDELMAN ("The Structure and Function of Antibodies") is professor at Rockefeller University. After studying as an undergraduate at Ursinus College (B.S., 1950) he received his M.D. from the University of Pennsylvania School of Medicine in 1954 and his Ph.D. from the Rockefeller Institute in 1960. In 1954 and 1955 he worked at Massachusetts General Hospital; in 1955 and 1956 he was a captain in the Army Medical Corps. He has been at the Rockefeller Institute and Rockefeller University since 1957, where in addition to his research and teaching he has served as associate dean of graduate studies.

ADDEKE H. BOERMA ("A World Agricultural Plan") is director-general of the Food and Agriculture Organization of the United Nations (FAO). Born in the Netherlands, he was graduated in 1934 from the Agricultural University in Wageningen, where he had specialized in horticulture and agricultural economics. In 1938 he entered government service in the Netherlands as officer in charge of preparing for food distribution in case of war. After the war he was member for the Netherlands of the Preparatory Commission for the study of Lord Boyd Orr's proposals for the establishment of a World Food Board; these proposals resulted in the establishment of the FAO. In 1948 Boerma was appointed Regional Representative of the FAO for Europe. Thereafter he held several other high posts in the organization. He was elected director-general in 1967.

WILLIAM A. PRYOR ("Free Radicals in Biological Systems") is professor of chemistry at Louisiana State University. After one year in high school he entered the University of Chicago and received the "Chicago Plan" Ph.B. degree in liberal arts in 1948 and a B.S. in chemistry in 1951. In 1954 he was awarded a Ph.D. in chemistry at the University of California at Berkeley. After working at the California Research Corporation, the University of California and Purdue University, he went to L.S.U. in 1963. Pryor's wife, Felicia, is associate professor of clinical psychology at L.S.U. and president-elect of the Louisiana Psychological Association.

H. E. HINTON ("Insect Eggshells") is professor of entomology at the University of Bristol. Born in Mexico, he studied at the University of California at Berkeley (B.Sc., 1934) and the University of Cambridge (Ph.D., 1939). After working for 10 years at the British Museum (Natural History) he went to the University of Bristol in 1949. He has published papers on a wide variety of topics in insect physiology, notably the respiratory adaptations of insects. ("From time to time I work on cryptobiosis, or the reversible suspension of metabolism. I have tried to show how the capacity to tolerate a total suspension of metabolism, which is almost universal among acellular organisms, supports theories of the origin of life on the land rather than in the sea.") In 1961 Hinton was elected a Fellow of the Royal Society of London.

LYNN WHITE, JR. ("Medieval Uses of Air"), is professor of medieval history at the University of California at Los Angeles. He was born in San Francisco in 1907, obtained a B.A. at Stanford University in 1928, an M.A. from Union Theological Seminary in 1929 and a Ph.D. from Harvard University in 1934. He taught at Princeton University and Stanford, served as president of Mills College for 15 years and has been at U.C.L.A. since 1958. He is a past president of the Society for the History of Technology, is now vice-president of the History of Science Society and sits on the councils of the American Historical Association, the Mediaeval Academy of America, the Renaissance Society of America and the American Association for the Advancement of Science.

ALEXANDER THOMAS, STELLA CHESS and HERBERT G. BIRCH ("The Origin of Personality") are respectively professor of psychiatry at the New York University School of Medicine, professor of child psychiatry at the same institution and professor of pediatrics at the Albert Einstein College of Medicine in New York. Thomas and Miss Chess are married. All three authors received their M.D. degree from the N.Y.U. School of Medicine. In addition to continuing with the work described in the present article, Thomas is engaged in the behavioral study of a population of children and adolescents and their parents from working-class Puerto Rican families and a cross-cultural comparison of this group with the middle-class, native-born families described in the article. Miss Chess is currently investigating temperament and other behavioral characteristics in a population of mentally retarded children living at home, and she is also directing a study of the behavioral and psychiatric characteristics of a large group of children with organic damage resulting from congenital rubella ("German measles"). Birch's major interests are mental retardation, the effects of early malnutrition on brain functioning and behavior and the psychophysiology of disadvantaged children.

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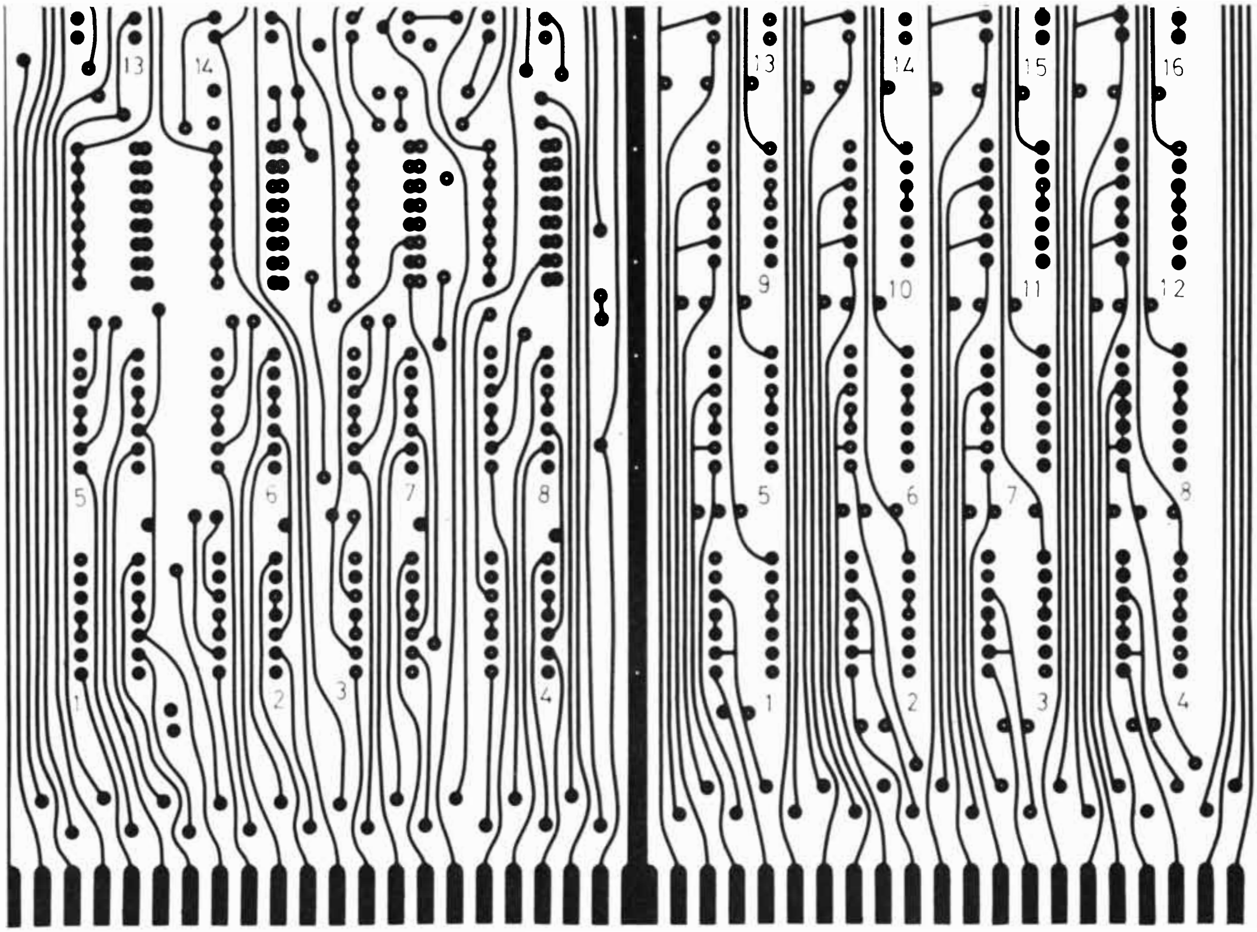

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Established 1845 SCIENTIFIC AMERICAN August 1970 Volume 223 Number 2

The Lunar Soil

A close analysis of a tablespoonful of soil from the sample gathered by the Apollo 11 astronauts at Tranquillity Base tells much about the structure and early history of the moon

by John A. Wood

The lunar landscape is not dominated by jagged rocky ridges, as were so often depicted in the illustrations accompanying articles and science fiction of past decades. Indeed, barren rock is all but absent from the surface of the moon; the observations of both manned and unmanned missions have revealed everywhere a rolling, hummocky terrain of plowed-up "soil"—more properly a loose, unconsolidated material mechanically similar to terrestrial soil. The lunar landscape resembles nothing so much as a World War I battlefield after intensive artillery bombardment, and for good reason: both kinds of terrain have been tortured by a rain of explosive projectiles.

In the case of the moon the projectiles are meteorites. Striking ceaselessly through all geologic time, meteorites have smashed hard lunar bedrock into pebbles, grit and dust. This loose debris has accumulated in a surface layer termed the regolith. The depth of the regolith must have increased with time, but at a diminishing rate; once some thickness of soil had accumulated, relatively few meteorite impacts were energetic enough to penetrate it and pulverize additional bedrock underneath. Less energetic impacts merely shifted the soil about and ground it finer.

The present thickness of the regolith can be gauged through careful studies of the shapes of lunar craters. Craters large enough and deep enough to have impinged on bedrock differ in appearance from lesser craters that affected only the regolith. In the broad, flat lunar maria, or "seas" (such as Mare Tranquillitatis, the site of the *Apollo 11* manned landing), the depths of craters that have reached bedrock indicate a regolith thickness of from five to 10 meters. The lunar highlands, older and therefore more heavily bombarded surfaces, are mantled by a much thicker regolith, perhaps 20 meters in depth.

Thus the *Apollo 11* astronauts Neil A. Armstrong and Edwin E. Aldrin, Jr., did not come within several meters of solid rock at Tranquillity Base, and the geology picks they had brought along for the purpose of chipping specimens off outcrops were superfluous. They stood and walked on top of the regolith and the lunar sample they returned was collected, with scoop and tongs, from this layer of rock debris.

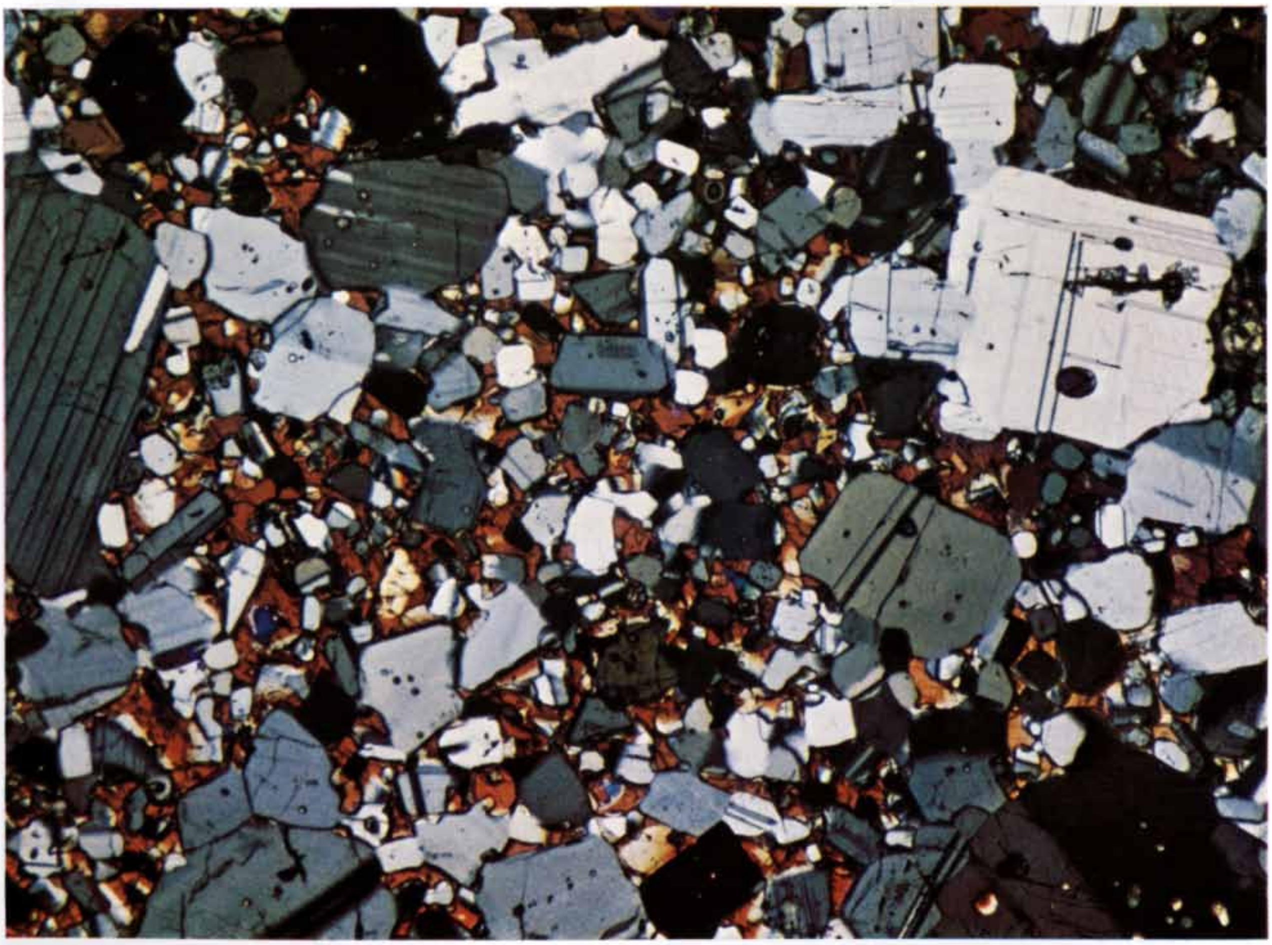
Their sample consisted of about 36 fist-sized rocks and 12 kilograms of more finely ground soil. Both rocks and soil have been studied intensively in the year since the *Apollo 11* mission. Our own group at the Smithsonian Institution Astrophysical Observatory has been working with 16 grams (about a tablespoonful) of the soil.

It might seem that the large rocks would be a more promising research material than the soil. After all, isn't the soil merely a ground-up form of those same rocks, and hasn't much of the character of the rock been obliterated in the grinding? Interestingly enough, the answer on both counts is no.

When a meteorite hits the moon and blasts out a crater, some fragments of lunar rock are thrown great distances. Rays—strips of debris "fallout"—can be seen extending from the crater Tycho completely across the visible face of the moon. Thus continued cratering not only produces soil but also to some degree mixes it over great distances. Although the soil at any given point undoubtedly consists largely of ground-up bedrock from directly underfoot, it must also contain some particles from far away. If these exotic fragments are rare, they might not be among the few large rocks

LUNAR LANDSCAPE in the vicinity of the crater Tsiolkovsky on the far side of the moon was photographed by the *Apollo 8* astronauts from an altitude of approximately 70 miles in December, 1968. The photograph gives a particularly good impression of the rolling, hummocky character of most of the lunar surface. The regolith, a surface layer of loose debris formed by repeated meteorite impacts, extends to a depth of perhaps 20 meters in such highland regions. The light color of the regolith in these regions suggests that it consists primarily of anorthosites, igneous rocks formed in a surface layer of molten magma.

LUNAR SOIL PARTICLES from the sample gathered at Tranquillity Base by the *Apollo 11* astronauts are shown before and after thin-sectioning. The glossy black fragments and spherules in the photograph at left are basaltic glasses; the white particle is an anorthositic glass; the slaggy gray fragments are basalts; the remaining particles include breccias (rocks composed of angular fragments cemented together). The particles in thin section in the photograph at right are arranged as nearly as possible in the same position and orientation as before sectioning. Micrographs made by shining light up through such sections from below enable petrologists to study the internal structure of the rock fragments. The particles measure roughly from one to three millimeters across.



ENLARGED VIEW of the thin section of an anorthosite particle found at the *Apollo 11* landing site shows the characteristic crystal structure of this lunar-highland rock. The large grayish crystals are plagioclase; the few small, well-defined crystals, usually purplish, are olivine; the brownish-orange matrix material is pigeonite. The width of the field is approximately two millimeters.

returned by an Apollo mission, yet the millions of small fragments that comprise the soil sample would certainly include some.

Much of the soil material has been ground and mixed beyond recognition, but this is not true of the coarser particles. If a sample of Tranquillity Base soil is shaken in a sieve with openings a quarter of a millimeter in diameter, about 75 percent passes through, and this fraction is indeed too finely ground to be very informative. The remaining 25 percent, however, is coarse enough for each particle to begin to be interesting as an individual. Each is a little rock in its own right, and each has a story to tell. Fortunately specialists in petrology, that branch of geology which deals specifically with rocks, are accustomed to working on a microscopic scale, and so the study of such tiny objects presents no particular challenge.

Petrologists work by grinding their rock samples (large or small) into slices thin enough to be transparent, so that they can be viewed under microscopes as light is beamed through them from below. This mode of observation reveals the interlocking patterns of mineral crystals. Precise chemical analyses of microscopic crystals in thin sections can be performed by an electron microprobe, and X-ray-diffraction procedures are used to assist in identification of the minerals. The ultimate goal of these investigations is to be able to draw parallels between lunar and terrestrial rock types. Since we know fairly well how the various terrestrial rock types came into being, we can hope through these analogies to understand something about the processes that formed and shaped the moon.

We might expect to find three classes of particles in the lunar soil: fragments of the meteorite projectiles whose impacts generated the soil, fragments of the rock immediately underlying the surface of the moon in a good state of preservation, and other rock fragments that have been badly damaged and altered by the energy of the meteorite impacts. From our 16-gram sample of lunar soil collected at Tranquillity Base we sectioned and examined some 1,700 coarse particles, and we observed particles belonging in all three categories.

Most important are the well-preserved fragments of lunar rock, because these would carry the record of the earlier and more profound geologic events that affected the moon, if such a record is preserved at all. We observed an astonishing diversity of rocky materials in the class of fragments that we judged to be "well preserved," but practically all fell into one of two broad categories: those similar to terrestrial basalts and those similar to terrestrial anorthosites. Both earthly analogues are igneous rocks. Basalts are volcanic rocks of widespread occurrence, lavas that issued in enormous volume onto the surface of the earth in times past, flowed out in layers of great lateral extent, cooled and solidified. The process still occurs periodically in the Hawaiian Islands, among other places. Anorthosites are much rarer and form in deeply buried masses of magma (melted rock).

I shall return to the significance of these two types of rock, but first it is worth looking at the class of "damaged" soil particles to learn about a process that still affects the lunar surface. Impact cratering does the damage, and of course the worst damage is done in a small volume of the regolith directly below the point of impact. There the soil is actually melted, and glowing drops and blobs are scattered in all directions. Droplets that cool and solidify in flight are preserved in the lunar soil as sleek glassy spherules. Other hot masses spatter on the lunar surface and congeal into intricate glassy shapes.

Farther from the point of impact, beyond the melted zone, is a larger volume of soil that is affected in a curious way. Instead of the soil particles' being ground even finer, as one might expect, the momentary impact pressure causes them to fuse to one another; loose soil is bonded into a solid mass called a breccia. In a later phase of the same cratering event the breccia is fragmented and scattered. Beyond the zone of breccia-welding a much larger volume of lunar material is simply broken or ground finer by the impact and is ejected from the crater.

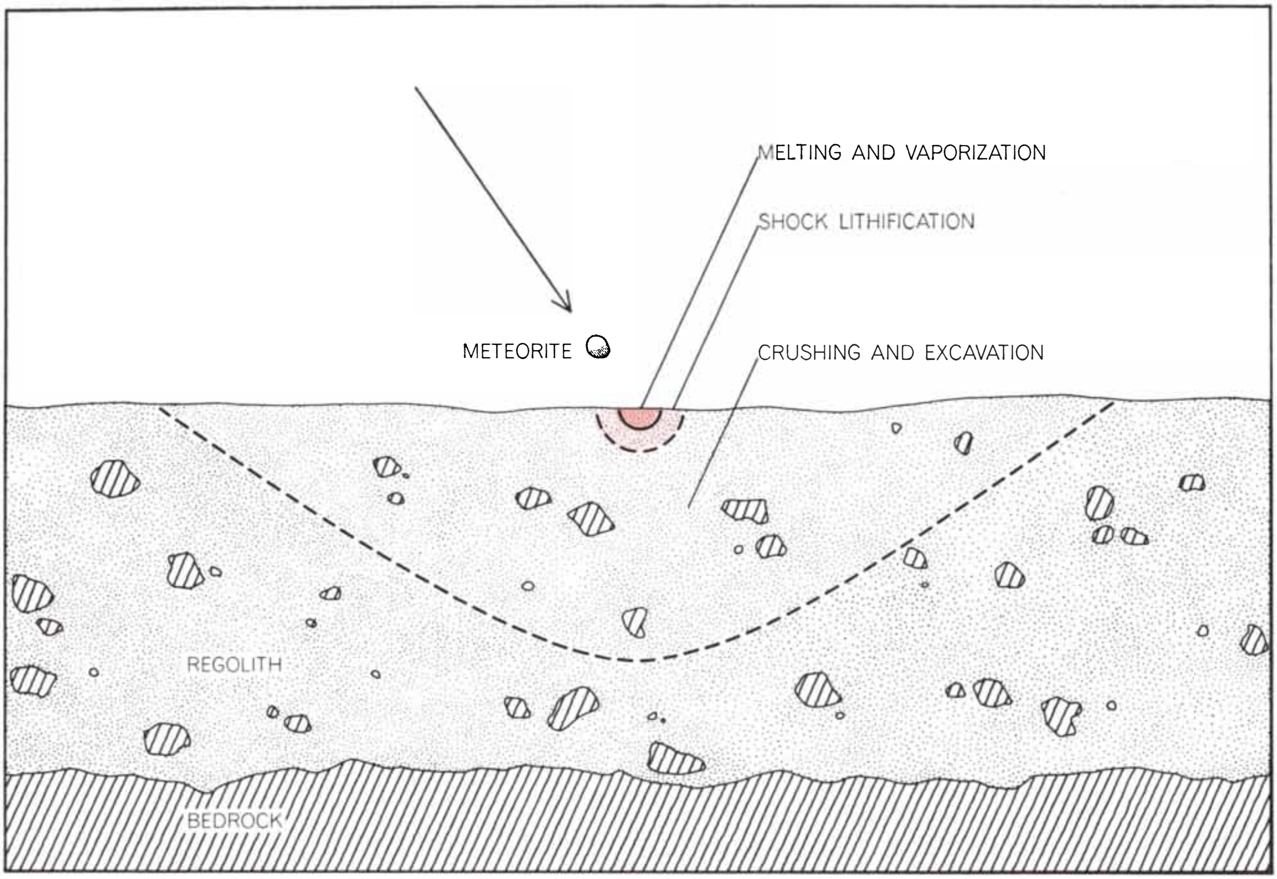
Glasses and breccias with compositions similar to both basalt and anorthosite are present in the Tranquillity Base soil; thus two distinctly different regoliths must exist somewhere on the moon, one in which impacts grind, pressure-weld and melt a basaltic parent rock, and another in which anorthositic bedrock is similarly affected.

The Tranquillity Base soil consists largely of basaltic rock, breccia and glass fragments. Anorthositic material is relatively rare (none of the large rock specimens collected were anorthositic). It seems clear that the basaltic fragments are samples of Mare Tranquillitatis itself, the bedrock underfoot. This confirms the view, previously held by a number of lunar investigators, that the maria must be vast lava-flow plains. The remarkable smoothness and dark color of the maria seemed to indicate this. Evidently the maria are low-lying regions, in many cases enormous impact craters (judging from their roundness) that were filled with basaltic lava early in the history of the moon.

The lavas crystallized into the mixture of minerals we observe today, the principal minerals being pyroxene, plagioclase and ilmenite. All three are common in terrestrial as well as lunar basalts, but the proportions differ; ilmenite, an oxide of iron and titanium, is a trace mineral in terrestrial basalts but constitutes 5 to 20 percent of lunar volcanics. The earliest accounts of the peculiarities of lunar rock, released soon after the *Apollo 11* sample was returned, stressed its extraordinarily high content of titanium; it is in the mineral ilmenite that most of the lunar titanium resides. Ilmenite is black and opaque, and it imparts a dark color to lunar basalts, particularly fine-grained specimens in which the black mineral is well disseminated. Basaltic soil and basaltic breccias, the finest-grained of all lunar materials, are even darker. The dark coloration of the lunar maria in general is undoubtedly attributable to ilmenite.

The color difference between lunar basalts and anorthosites is not subtle. The latter are much lighter, almost white, because they consist largely of the white mineral plagioclase (a calcium-aluminum silicate) and contain little or no ilmenite. If basalts in the lunar soil are derived from the dark maria, it is tempting to suppose that anorthosites are samples of the light-colored highlands. A highland region lies only 50 kilometers to the south of Tranquillity Base, and it seems inevitable that some amount of crater ejecta from the highlands would have contaminated the Tranquillity Base soil during the long history of the lunar surface. The proportion of contaminant in the soil would not be large, of course; 5 percent or so (the amount of anorthosite present) seems a reasonable level.

Firm and dramatic support for the hypothesis that the highlands are anorthositic comes from an unmanned spacecraft that landed on the moon 18 months before Armstrong stepped gingerly onto the regolith. The Surveyor program sent seven ungainly spacecraft to land on the moon, and the last three Surveyors carried instruments designed to measure the chemical composition of the lunar



EFFECTS OF TYPICAL METEORITE IMPACT on the lunar surface material are indicated in this cross-sectional diagram. The meteorite shown is about to blast a crater in the regolith but is too small to affect the bedrock. A small volume of soil directly below the point of impact (*dark color*) will be melted, creating a rain of glowing drops of rock that will solidify to form glasses. Farther from the point of impact is a larger volume of soil (*light color*) in which the momentary impact pressure will cause the soil particles to fuse to one another, forming a solid mass, called a breccia, that will then be fragmented and scattered. Beyond this zone a still larger volume of material (*broken black line*) will simply be broken or ground finer by the impact and ejected from the crater.

surface at the landing site. These instruments, which were developed by a group headed by Anthony Turkevich of the University of Chicago, utilized an ingenious analytical technique known as alpha backscattering. Alpha particles emitted by a tiny sample of radioactive curium 242 were allowed to impinge on the lunar surface under a landed Surveyor spacecraft; the briskness with which they bounced back into an overhead particle detector could be interpreted in terms of the massiveness of the lunar atoms they had knocked against. Heavy iron atoms in the lunar regolith returned the alpha particles at higher velocities than lighter aluminum atoms did, for example, just as a tennis ball bounces at a faster speed from a brick wall than from the wall of a canvas tent. From the total spectrum of return velocities of alpha particles recorded by the Surveyor instrument, the concentrations of all the principal atomic species in the area of regolith that was bombarded could be deduced.

Surveyor 5 landed in Mare Tranquillitatis, only 25 kilometers from what was to be Tranquillity Base, and returned an analysis indicating that the soil was made up of titanium-rich basalt. The *Surveyor* analysis was subsequently confirmed in detail when *Apollo 11* samples were chemically analyzed in terrestrial laboratories. *Surveyor 6* landed in Sinus Medii, another mare site, and again reported a surface of basaltic composition.

Surveyor 7, however, was sent to the lunar highlands. It landed on the blanket of ejecta surrounding the crater Tycho, and thus analyzed a mixture of rock fragments that had been dredged up from kilometers under the highlands when Tycho was excavated. The analyses it returned indicated a material quite different from the basalts at the other two sites; in fact, it has turned out that the Tycho compositions are a good match for the composition of lunar anorthosite fragments our group has analyzed with our electron microprobe [*see illustration on page 20*].

Anorthosites have a lower specific gravity than mare basalts (about 2.9 grams per cubic centimeter v. about 3.3 grams for *Apollo 11* basaltic rocks). This finding is in agreement with earlier predictions that the lunar highlands must be underlain by material less dense than the material under the maria. These predictions were based on measurements of lunar gravity. Consider a moon made of only one type of rock, with a uniform specific gravity. As a spacecraft flew over the surface of the moon it would feel a stronger gravitational tug as it passed over a highland region than when it was above a mare, simply because there was an extra thickness of rocky material directly below it in the former case, and this additional mass would have supplied additional gravitational attraction [*see illustration on page 21*].

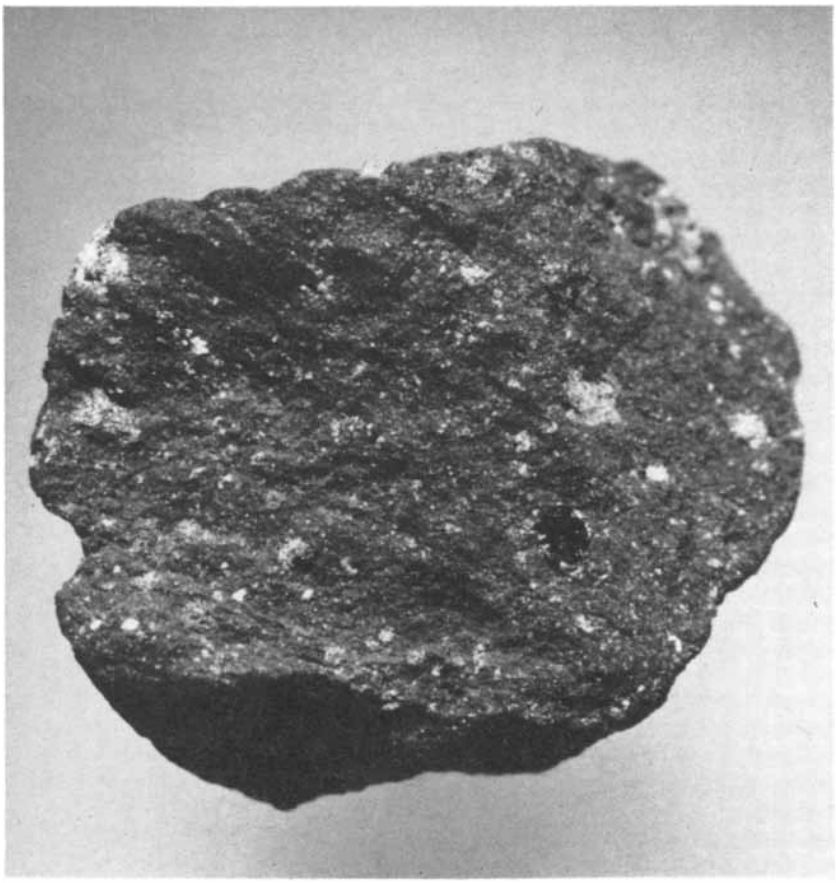
Gravity is measured in terms of how rapidly it can accelerate the rate of fall of an object released under its influence; one gal (a unit of gravity named for Galileo) is defined as an acceleration of one centimeter per second per second. On this standard the lunar highlands, which are an average of about 1.4 kilometers higher than the mare surfaces, ought to exert an extra .2 gal (or 200 milligals) of gravitational attraction on a spacecraft as it passes over, compared with the gravitational pull over mare regions. In other words, there should be a positive gravity anomaly above the highlands.

But there isn't. A series of spacecraft (the Lunar Orbiters) were placed in orbit about the moon in 1966 and 1967, chiefly to perform photographic reconnaissance, but they also showed variations in lunar gravity. This was revealed not by any type of gravity-sensing instrument carried in them but rather by the motions of the spacecraft themselves, which were tracked with great accuracy from the earth. A spacecraft passing over a region of gravity excess should be deflected downward slightly from its normal orbit. Positive gravity anomalies (the "mascons") were found by this means, but they exist in certain of the maria, not in highland regions [see "The Exploration of the Moon," by Wilmot Hess, Robert Kovach, Paul W. Gast and Gene Simmons; SCIENTIFIC AMERICAN, October, 1969]. The lunar highlands do not contain excess mass.

This can only mean that our initial assumption of a uniform specific gravity for lunar rocks was wrong. If the highlands were composed of and underlain by a material of lower specific gravity than the maria are, there need be no gravitational anomaly. The excess mass represented by the additional height of the highlands would be offset by a deficiency of mass in the root zone under the highlands, owing to the fact that the specific gravity of these roots is lower than that in the adjacent maria. This is equivalent to saying the highlands float in denser rock of the mare type, with only a small fraction of their volume above the surface, like an iceberg. Such an object is said to be in buoyant equilibrium, and it displays no significant gravitational anomaly. (The allusion to floating highlands does not imply that they were ever necessarily immersed in molten magma. Cold solid rock under stress tends to creep, and over very long periods of time it behaves as an extremely viscous fluid.) A plate or "raft" of anorthosite would have to be about 10 kilometers thick for the uppermost 1.4 kilometers (the mean height of the highlands) to float above the surface of a "bath" of basalt such as that found at Tranquillity Base.

The discovery that anorthosite is one of the principal lunar rock types took everyone by surprise. Terrestrial rock-forming processes have not produced important quantities of it. The only known mechanism that is capable of generating anorthosite is crystal fractionation, a process that depends on the fact that natural rock materials do not melt (or freeze) at a single well-defined temperature, as simpler substances such as water and pure iron do, but over a range of temperatures. As a typical rock material is heated, the first melt liquid appears at roughly 1,000 degrees Celsius. The composition of the liquid differs from that of the rock as a whole: certain low-melting elements (sodium, potassium, silicon, aluminum and iron) are enriched in the liquid. With rising temperature more of the rock is melted. The last surviving solid crystals are enriched in the more refractory elements, principally magnesium and calcium. Finally, several hundred degrees above the temperature at which melting began, the rock is completely liquefied.

The process works the same in reverse, as a magma or lava is cooled. The first crystals to appear are enriched in magnesium and calcium. For a broad range of realistic magma compositions these early crystals would consist of the minerals plagioclase (calcium-aluminum silicate) and olivine (magnesium-iron silicate). Now, note that the crystals in such a system would not in general have the same specific gravity as the liquid surrounding them. If the magma were quiescent, and if it were cooled slowly enough, the crystals would tend to sink (or float, depending on the specific gravity involved) and accumulate on the floor (or against the ceiling) of the magma chamber. The process is known to



LUMP OF BASALTIC BRECCIA from the *Apollo 11* landing site in Mare Tranquillitatis measures about 16 millimeters across. Numerous smaller rock and mineral fragments, including a split-open glass spherule (*black spot at lower right*), can be seen embedded in the breccia fragment. The characteristic dark color of such lunar mare, or lowland, rocks is attributable to the presence in them of the titanium-rich mineral called ilmenite.

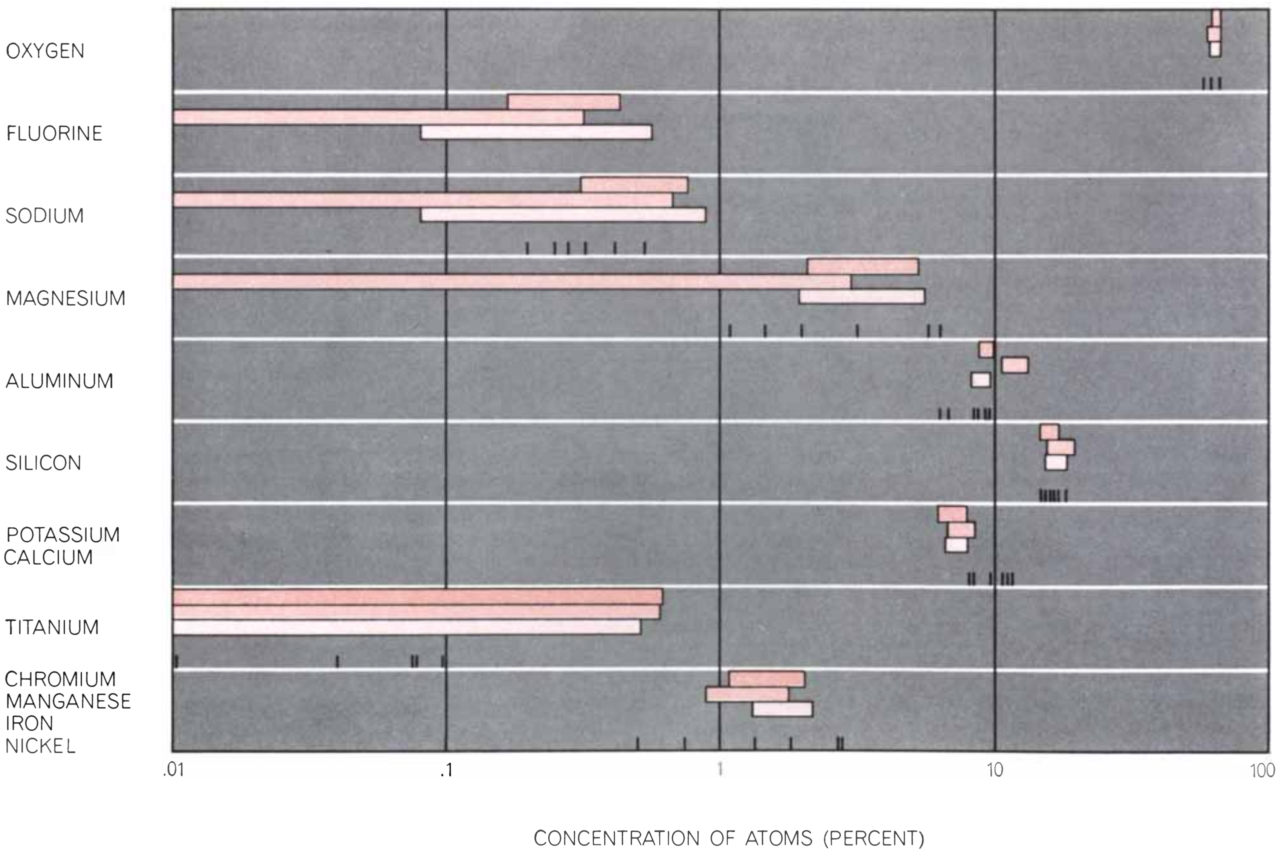
work on the earth: great magma systems that crystallized long ago and have been laid open to geologic study by erosion are found to contain layers of accumulated olivine crystals and layers of plagioclase crystals. Plagioclase-rich rocks from such layers are by definition anorthosites.

The lunar anorthosite must have been formed by such a process. Since it occurs as a layer at the surface of the moon (in the highlands), we must suppose the magma system that gave rise to it was not confined underground, as the terrestrial systems were, but was awash on the surface of the moon at some early time. We must also suppose that plagioclase crystals tended to float rather than sink in this magma. The unusually high specific gravities found for lunar-mare basalts (which bear some relation to the magma in which the hypothetical floating or sinking occurred) make flotation seem plausible enough.

Light-colored highland terrain extends completely around the moon, interrupted by maria only on the earthward lunar face. Our deduction that the highlands are anorthositic is applicable only to the highlands adjacent to Mare Tranquillitatis (and even there it is of course conjectural). Nonetheless, the simplest and most plausible assumption at this stage is that the processes that created the near-surface structure of the moon operated with a fair degree of symmetry. This conception leads us to suppose that a "crust" of anorthosite envelops the moon.

It was already obvious from the basaltic nature of most of the lunar sample that high temperatures had prevailed and some melting had occurred on or in the moon, but consideration of the anorthosite problem leads us to the further conclusion that heating and melting affected the early moon profoundly. Crystal fractionation in a surface magma had to supply approximately 10 kilometers of floating plagioclase crystals (anorthosite). Since this magma contained elements in addition to those needed to crystallize plagioclase, more than 10 kilometers of liquid was needed to produce 10 kilometers of anorthosite; 20 kilometers or more of molten rock is indicated.

Even these 20 kilometers do not define the limit of melting in the moon. We do not know the overall composition of the moon, but we can exclude the possibility that it contained anything like 50 percent of plagioclase throughout, be-

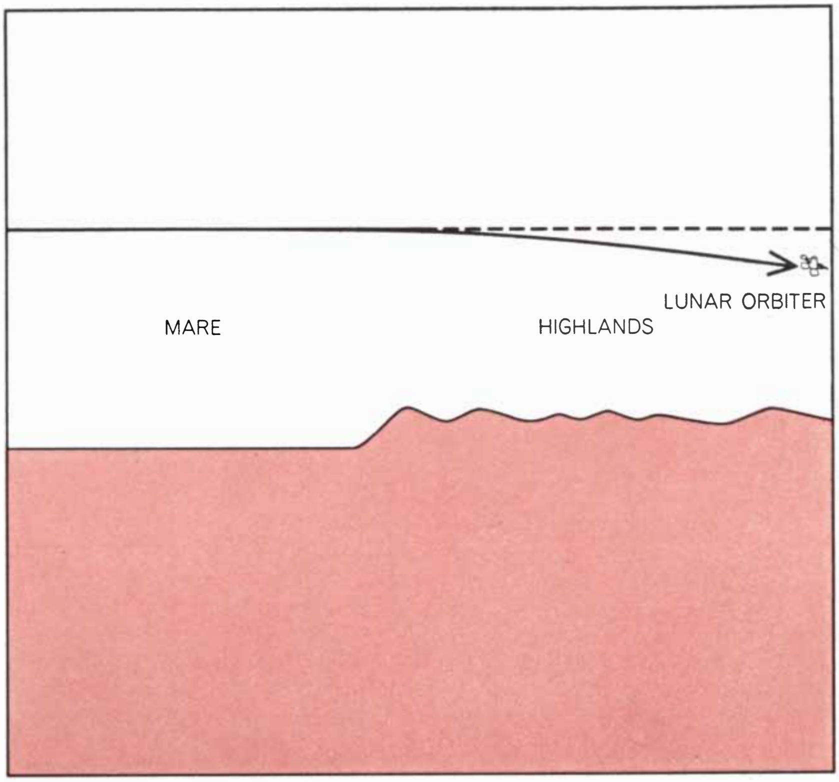


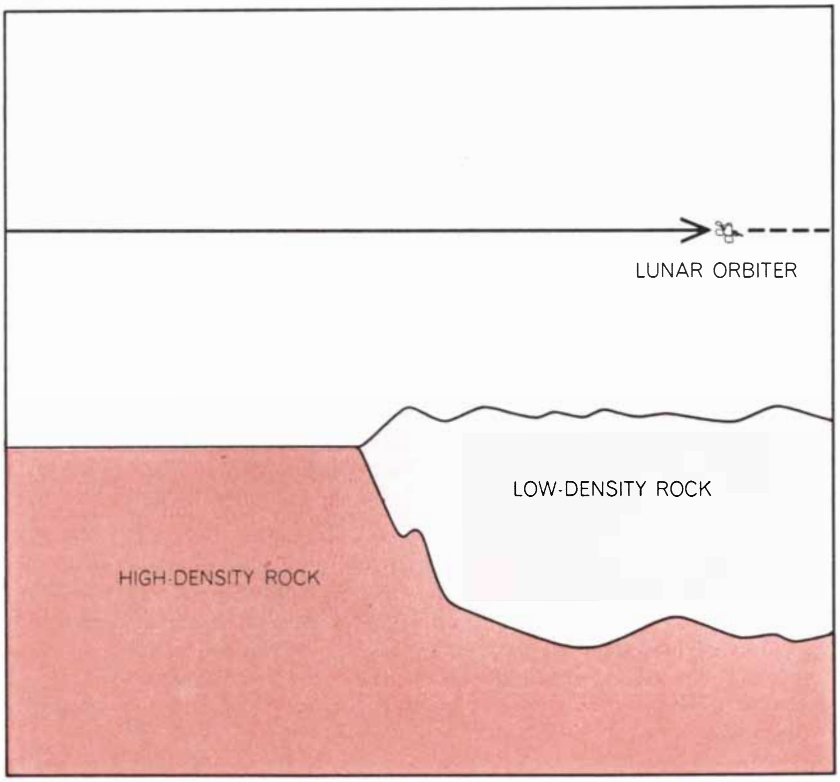
COMPOSITIONS of the lunar highland material analyzed on the moon by the unmanned *Surveyor 7* spacecraft (*colored bars*) and lunar anorthosite fragments analyzed by the author and his colleagues at the Smithsonian Astrophysical Observatory (*black lines*) are compared in this chart. *Surveyor 7* used a technique called alpha backscattering, developed by a group headed by Anthony Turkevich of the University of Chicago, to measure the chemical composition of the surface soil (*dark color*), surface rocks (*intermediate color*) and the soil at the bottom of a small trench dug by a mechanical shovel on the spacecraft (*light color*). The data are entered here as horizontal bars instead of lines to indicate the degree of uncertainty of the measurements. When the range of uncertainty includes the possibility of zero concentration in the *Surveyor 7* samples, these bars disappear off the left side of the logarithmic chart. The *Apollo 11* measurements were made by means of an electron microprobe in the author's laboratory and are indicated as point values. The close match between the two sets of data supports the view that the anorthosite fragments discovered at the *Apollo 11* site originated in the nearby lunar highlands. Fluorine was not detected in the *Apollo 11* anorthosites.

cause pressures at any great depth in the moon would transform such feldspar-rich rock into an assemblage of garnet and pyroxene minerals of such high aggregate specific gravity as to be irreconcilable with the known overall specific gravity of the moon. (This value is derived from astronomical determinations of the moon's mass and dimension.) The plagioclase content of the moon must be small. A reasonable assumption is that the moon's overall composition bears some resemblance to that of chondritic meteorites, ancient rocks that are generally held to be samples of planetary matter as it first accreted in the solar system. Such a moon would contain roughly 5 percent of calcic plagioclase. It would have to be ransacked to a depth of about 200 kilometers to obtain a sufficient abundance of the elements needed (aluminum is the most critical) to create a 10-kilometer thickness of anorthosite.

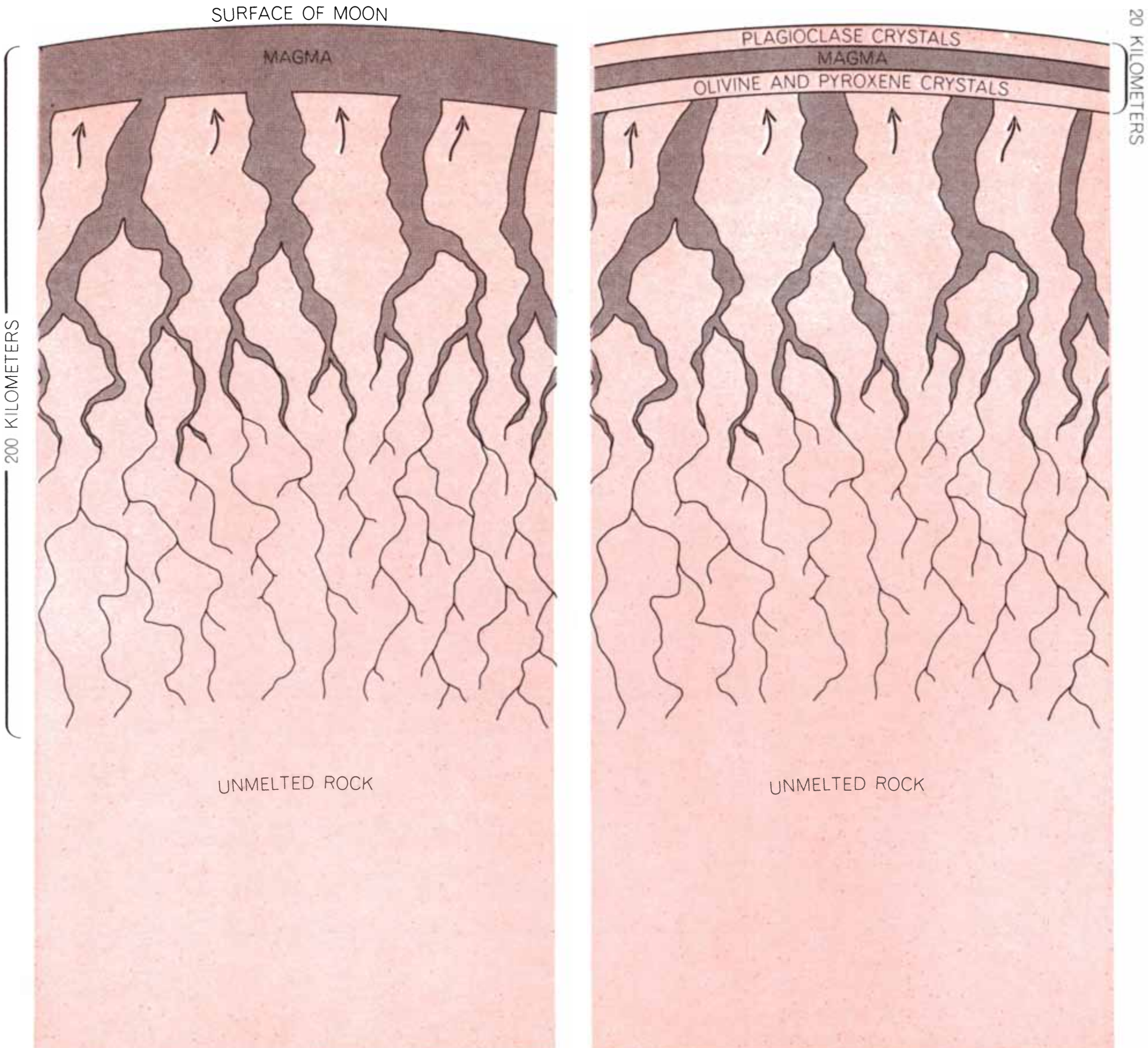
This process was probably accomplished by means of partial melting of the rock. I have mentioned the fact that rock does not melt at a single temperature but over a range of temperatures. If one pictures a moon heated and completely melted at the surface but left relatively cool and completely solid inside, it follows that there must be a transitional layer between these two zones where the rock was partially melted. The melt fraction in this layer would be enriched in plagioclase-forming elements (aluminum and silicon). In fact, it would contain much or all of the plagioclase that the rock in the zone of partial melting had to offer. Rock expands on melting by about 10 percent, becomes less dense than the solid it was derived from and so tends to float above the solid residue left after partial melting. This explains why plagioclase-rich melts from considerable depth would tend to rise and join a magma layer at the surface of the moon. In short, when partial melting occurs, plagioclase-forming elements are concentrated in the melted fraction, and this plagioclase-rich melt tends to be squeezed up toward the surface by differences of specific gravity.

It therefore appears that the moon must have been very hot to a considerable depth at some stage in its history. It would have had to be hotter than about 1,000 degrees C., probably to a depth of 200 kilometers or more, in order to generate a quantity of magma adequate to the task of separating (by means of crystal fractionation) a 10-kilometer raft, or scum, of floating plagioclase crystals. This would mean that melting occurred





TWO POSSIBLE CONFIGURATIONS of the lunar interior near the surface are depicted here, along with a representation of the gravitational effect of each on the orbit of a spacecraft (such as the Lunar Orbiter) passing over. At top the rock is homogeneous in composition and specific gravity; the additional mass in the highlands would deflect the spacecraft downward in its orbit. At bottom the highlands are a "raft" of low-density rock "floating" in higher-density material; the spacecraft would not be deflected. Accurate tracking of the Lunar Orbiters from the earth revealed positive gravity anomalies in certain lunar maria but not in the lunar highlands; thus the bottom picture is closer to the truth.



PARTIAL MELTING in the outermost 200 kilometers of the moon at some stage of its history would probably have been required to provide a sufficient abundance of the elements needed to create a 10-kilometer thickness of anorthosite in the lunar highlands. The melted material (*color*) would be squeezed up along rootlike channels to join a layer at the surface (*left*). At some later stage (*right*) the surface layer would have cooled and partially crystallized, with different minerals separating by crystal fractionation into layers. The uppermost layer of floating plagioclase crystals would, after complete solidification, comprise the rock anorthosite.

in a third or more of the volume of the moon.

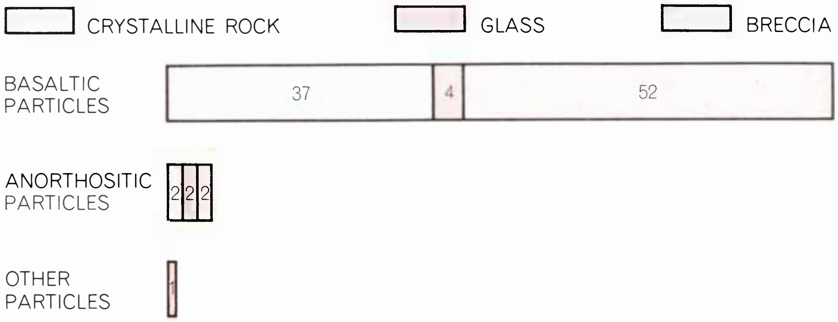
Planets contain radioactive isotopes of uranium, thorium and potassium, and we know that as these decay they generate heat and raise the temperature inside the planet. There is reason to think, however, that this is not the heat source responsible for melting our hypothetical 20 kilometers of surface magma. Decay of the radioactive isotopes named is slow, the temperature rise attributable to them is gradual, and any melts generated by them would issue onto the lunar surface in small increments, each of which could cool and solidify separately. We need a way of heating the outermost volume of the moon rapidly and causing wholesale melting in one fell swoop, so that 20 kilometers of magma could be present at the surface, all in the liquid state at one time. Only then could crystal fractionation bring 10 kilometers of plagioclase crystals together into one layer.

There are several physical mechanisms that might have generated heat swiftly and in substantial amount in the moon. All would have operated in earliest times, while the moon was in the process of formation or immediately afterward. One is energy of accretion. If the moon formed by accretion of smaller particles or planetesimals, as many suppose, each particle would strike the lunar surface with a certain amount of kinetic energy, some fraction of which would be converted to heat energy. If impacts were sporadic and accretion gradual, this heat energy would be dissipated into space as fast as it was generated. If accretion were rapid, however, much of the energy would be trapped in the moon. A 100 percent retention of accretional energy would promote melting in the outer 500 kilometers of the moon. (Particle impacts become harder as a planet grows in size and attracts the particles more forcefully, so that accretional heat generation is most effective in the outermost layers of the planet.) No one knows, however, if accretion proceeded rapidly enough to cause important heating effects in the moon.

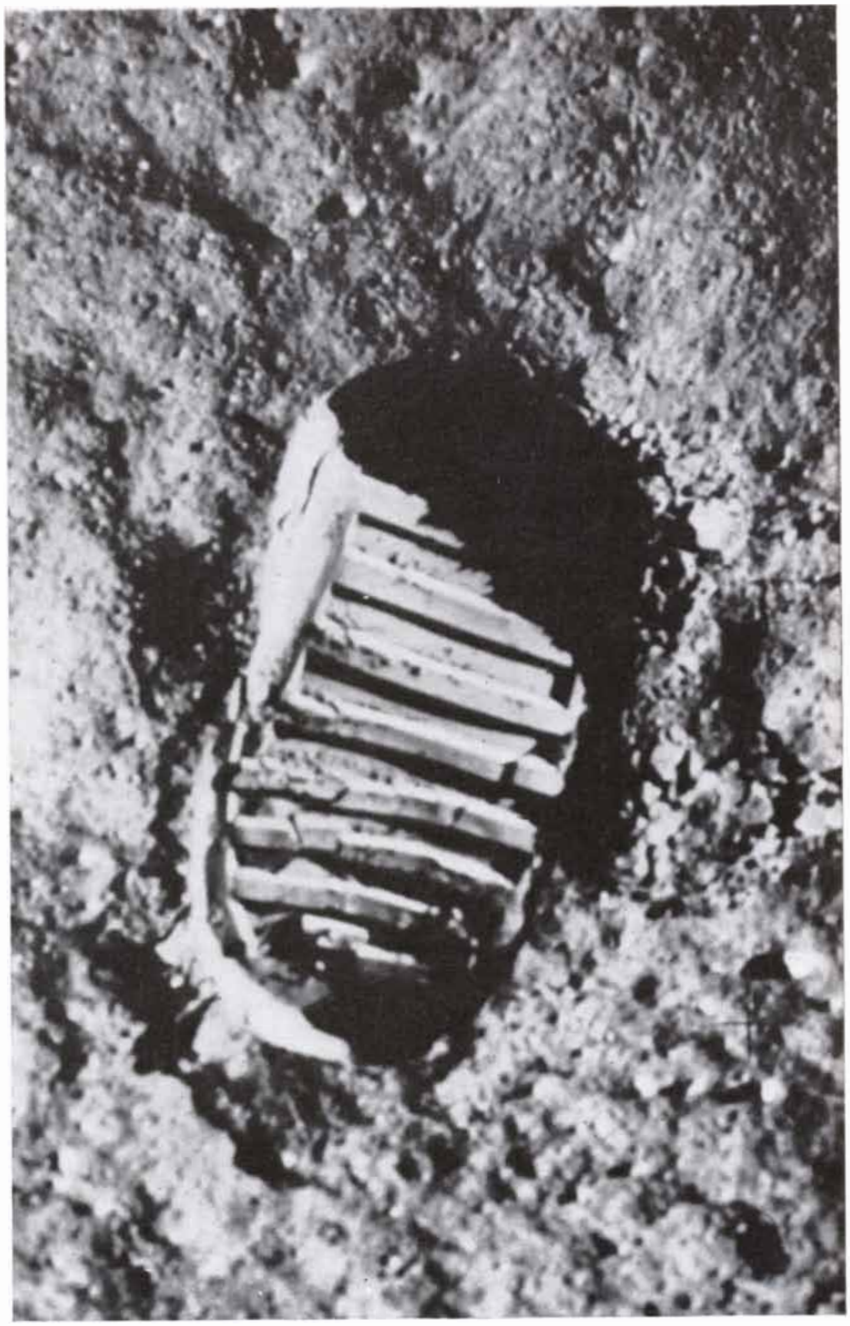
Another possibility is electrical heating. The solar wind, a plasma of charged particles that sweeps past the moon, induces electric currents in the moon that generate heat. The amount of heat generated by the present solar wind is trivial, but there is evidence from astronomical observations of young stars that the solar system, in common with other stellar systems, passed through a stage when plasma was being expelled from the sun at a vastly greater rate than it is today. The electrical effects of such a solar wind might have melted portions of the moon, and again it is the near-surface portion of the moon that would have been affected.

Still another possibility is extinct radioactivity. Possibly when the elements of the solar system were formed there were, in addition to the observed stable and long-lived radioactive isotopes, short-lived isotopes that have long since decayed beyond the possibility of being observed by us today. These might have generated large amounts of heat in the early planets. We do not know at this point how the moon came to be heated and to some degree melted in early times, but it seems clear that it did happen.

It is remarkable that a tablespoonful of soil can tell us so much about the structure and early history of the moon. We are still, however, a long way from a satisfactory understanding of that body. Every answer provided by the lunar samples has raised several troublesome questions. For example, why are there dissimilarities between *Apollo 11* and *Apollo 12* materials? Is one site more highly evolved than the other, or are the underlying sectors of the moon fundamentally different? If several moonlets coalesced to form the moon, and if the moon has not subsequently been wholly melted and mixed, each moonlet sector might preserve compositional autonomy to the present day. If the melting event that gave rise to an anorthositic layer occurred in earliest times (about 4.6 billion years ago), why are the lunar basaltic rocks as young as they are (about 3.4 billion years by radioactive-dating techniques)? Heat-flow calculations show that the postulated lunar surface magma system could not remain hot and molten for as much as a billion years. Did the lunar basalts derive from later partial melting deep in the lunar mantle, and not from the same magma system as the anorthosites? We await with impatience the samples and answers that future Apollo missions will provide.



TYPES OF SOIL PARTICLES found in the Tranquillity Base sample analyzed by the author's group are indicated in this bar chart in terms of their relative percentages.



PHOTOGRAPH OF A FOOTPRINT of one of the *Apollo 11* astronauts gives a good idea of the consistency of the lunar surface material in the vicinity of the Tranquillity Base site.

TANDEM VAN DE GRAAFF ACCELERATORS

Based on the principle of the electrostatic belt generator invented by Robert J. Van de Graaff in 1931, these versatile and dependable machines are ideal for studying certain kinds of nuclear reactions

by Peter H. Rose and Andrew B. Wittkower

In the early days of nuclear physics investigators were content to work with beams of comparatively low-energy, or slow, particles emitted by radioactive sources. By the late 1920's, however, it became apparent that certain important questions could only be answered by experimenting with beams of high-energy, or fast, protons and alpha particles (helium nuclei), generated by some kind of accelerator. Since the particles to be accelerated were charged it was clear that high voltages could be employed to give them high energies; unfortunately power supplies giving direct-current voltages above 100 kilovolts were not available at the time.

Three ingenious solutions to this problem soon appeared. At the Cavendish Laboratory of the University of Cambridge, John D. Cockcroft (in association with E. T. S. Walton) invented a voltage-multiplying circuit, which he used to become the first to split the atom. Meanwhile Robert J. Van de Graaff of Princeton University worked out a quite different solution: he invented an electrostatic belt generator, which because of its greater voltage capacity rapidly superseded the Cockcroft-Walton power supply for many research purposes.

Ernest O. Lawrence of the University of California at Berkeley chose yet a third route: he avoided the difficulty of reaching a high d.c. voltage by combining a modest alternating voltage with a magnetic field, thus using the same voltage repeatedly to accelerate particles to high energies. His cyclotron paid for the repeated use of this voltage by having an output beam whose energy is difficult to control; moreover, instead of providing continuous beams devices built on the cyclotron principle give short bursts of particles. Nonetheless, the cyclotron immediately made accessible extremely high energies, and its direct descendants, which include the huge proton and electron synchrotrons, have played a central role in the development of modern nuclear physics.

For many applications, however, the special advantages of the lower-energy d.c. machines—greater beam uniformity and variability, lower cost and comparative ease of operation—have remained predominant. This demand has resulted in the development of a succession of improved d.c. accelerators, culminating in the tandem, or charge-changing, machine, which is basically an elaboration of Van de Graaff's original belt-charging scheme. The latest models of this device have attained energies in excess of 20 million electron volts. As the energies available from such accelerators continue to rise they promise to make important new contributions to the study of nuclear reactions.

For the original d.c. generators, reaching potentials above a million volts at first seemed to be an intractable problem. Air at atmospheric pressure can only support voltage gradients somewhat less than 20 kilovolts per inch, which meant that to reach multimillion-volt potentials these machines had to be of enormous size. The largest of the conventional d.c. generators, built by Van de Graaff in 1936, had spherical terminals 15 feet in diameter and was housed in an airship hangar [*see illustration on page 26*].

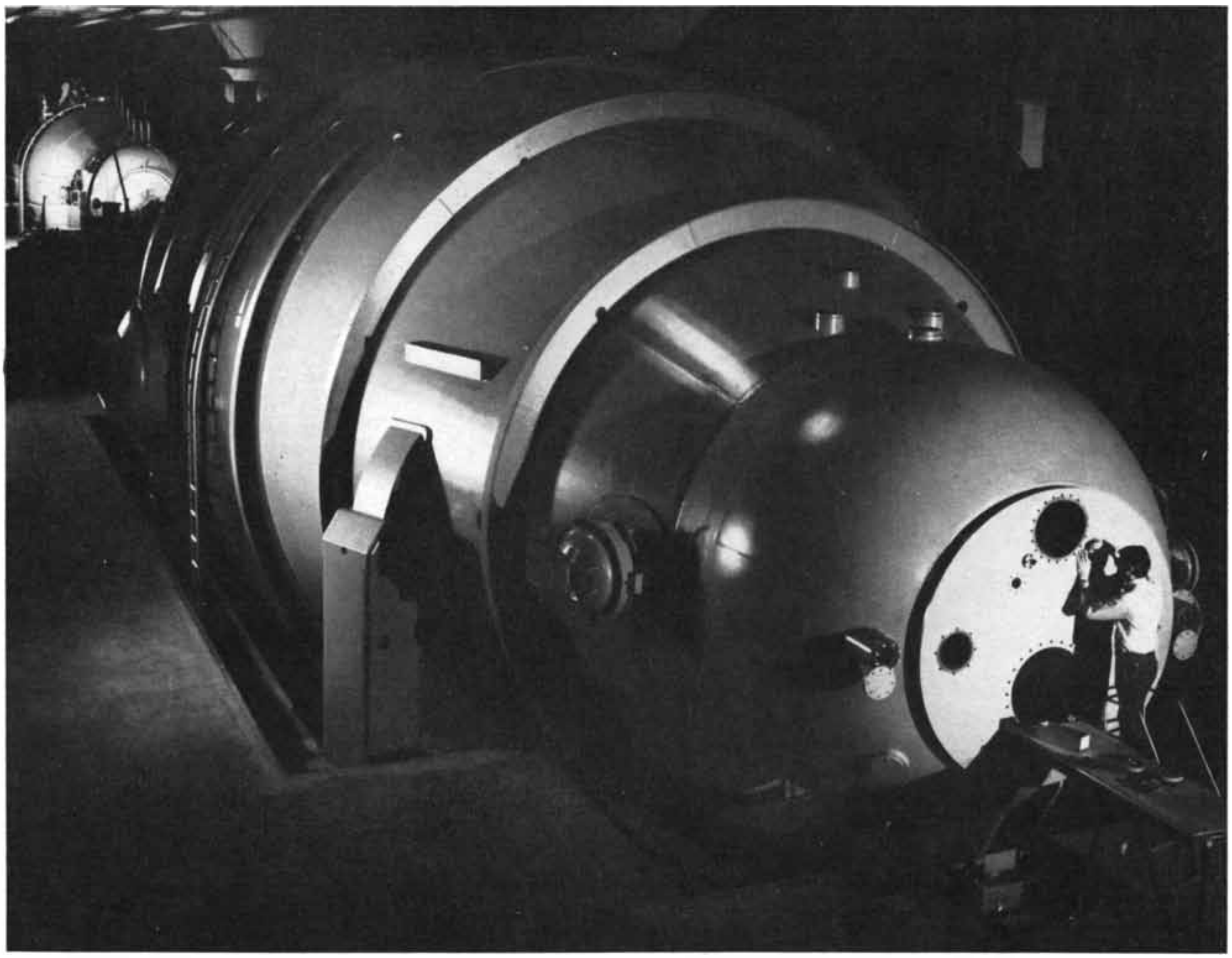
The high voltage attained by this machine was produced by transporting electric charge from the grounded end of a fast-moving belt into the hollow insulated terminal. The charge was sprayed onto the belt from sharply pointed electrodes and was removed by a metal collector screen that brushed lightly against the belt inside the terminal. At any instant the terminal potential of such a machine depends on the amount of charge stored in the insulated sphere, and it reaches and maintains a steady potential when the charging current delivered by the belt just matches the maximum-load current from the terminal. This large air-insulated machine achieved voltages as high as 5.4 million volts for short periods. This voltage, however, was not available directly for the acceleration of particles, and many changes had to be made before a d.c. accelerator was operational, and then its maximum voltage was lower. Much of the difficulty was associated with the fact that in this early model the ions were accelerated in a vacuum; although the acceleration tube was more than 26 feet long, sparking near the terminal and along the tube limited the effective voltage to about 2.7 million volts.

Because of the difficulty of obtaining high d.c. voltages there was considerable excitement in 1929 when Bergen Davis and Arthur H. Barnes of Columbia University announced that they had found a method of attaching electrons to fast alpha particles, thereby neutralizing the positive charge of the alpha particles. This opened the possibility of obtaining very high energies by allowing the particles to drift while neutral to a high-voltage terminal, stripping off the electrons in the terminal, accelerating the alpha particles to "ground" voltage, neutralizing them by adding electrons again and so on until the desired energy was reached. Unfortunately the experimental results of this study were misleading, and "charge-changing" as a means of accelerating particles was abandoned for several years. It is interesting that Van de Graaff, the man eventually responsible for developing the tandem accelerator when the technology was ready, was among the first to realize the significance of these experiments. He witnessed a demonstration of the Davis-Barnes device in 1930 at Columbia and at first found it quite convincing. In spite of the need to disregard the erroneous experimental results, Van de Graaff's early exposure to charge-changing probably stayed in his mind and made him ready when the practical opportunity came. This, however, is getting ahead of the story.

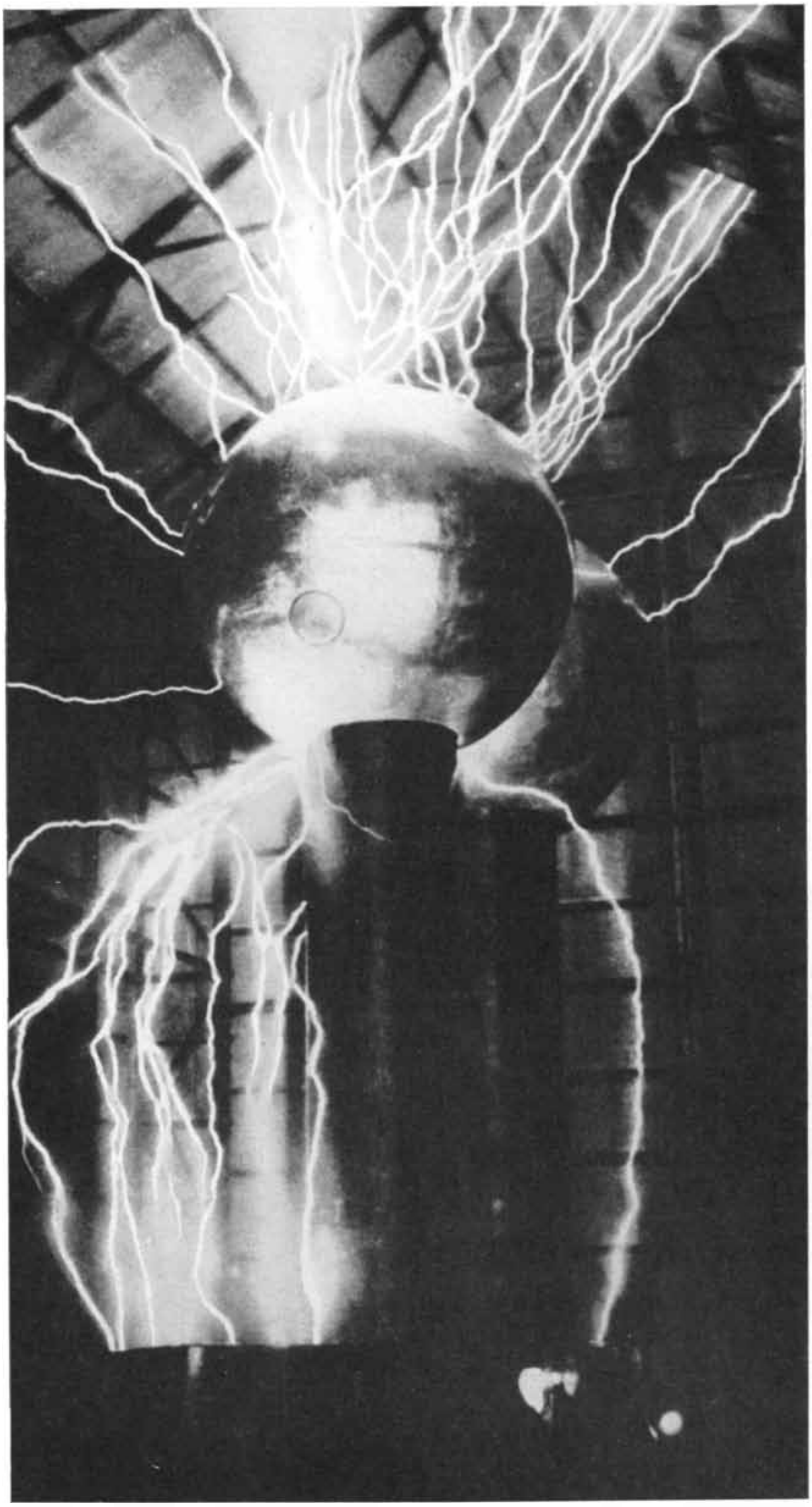
Subsequent studies of electrical discharges in gases led to the discovery of free, stable negative ions, and in fact very weak beams of these particles were extracted from such discharges and used in collision experiments. In 1937 Willard H. Bennett of Ohio State University was awarded a patent for an accelerator that made use of charge-changing to double the energy of a beam of particles. In his scheme a beam of negative ions is accelerated to a terminal where electrons can be removed from the negative ions by collisions with a thin foil [*see illustration on page* 27]. The resulting positive ions are accelerated by the second gap and strike the target with an energy corresponding to acceleration through an accelerator with twice the voltage.

Unfortunately negative ions were still a laboratory curiosity in 1937. Sources of negative ions intense enough to satisfy the nuclear physicist were not available, and anyway not many physicists of the era read patent literature. As a result Bennett's proposal was apparently forgotten.

In any case the urgency of military research projects during World War II did not allow speculative accelerator development, and the idea of using negative ions to double the effective voltage of a d.c. accelerator stayed in limbo until the circumstances were right for its exploitation. The war, however, was responsible for the development of much new technology that led to many significant improvements in the d.c. accelerator and was eventually applied to the tandem accelerator. Much of the new nuclear information required to build the atomic bomb, for example, was acquired using pressurized Van de Graaff accelerators developed by R. G. Herb and his associates at the University of Wisconsin. In addition, at the Massachusetts Institute of Technology, Van de Graaff, John G. Trump and others developed a highly sophisticated compact electron accelerator for radiographing



TWO TANDEM VAN DE GRAAFF ACCELERATORS are shown being assembled in the heavy-ion laboratory of the High Voltage Engineering Corporation. The machine in the foreground is the most powerful tandem accelerator built to date; designed to attain terminal voltages of 20 million volts, it has already surpassed 21 million volts in operation. It was intended to be used in conjunction with a 13-million-volt machine (*background*) to accelerate uranium ions to energies high enough to interact with a uranium target located inside the high-voltage terminal at the center of the second machine. The experiment has not yet been carried out.



LARGEST DIRECT-CURRENT GENERATOR was built in 1936 by Robert J. Van de Graaff, then at the Massachusetts Institute of Technology. The machine, which was housed in an airship hangar, produced a high voltage by transporting electric charge from the grounded end of a fast-moving belt into one of two terminals, which consisted of hollow insulated metal spheres each 15 feet in diameter. Although this large air-insulated machine achieved voltages as high as 5.4 million volts for short periods, it was not available directly for the acceleration of particles. When adapted for this purpose, sparking near the terminal and along the acceleration tube limited the voltage to about 2.7 million volts.

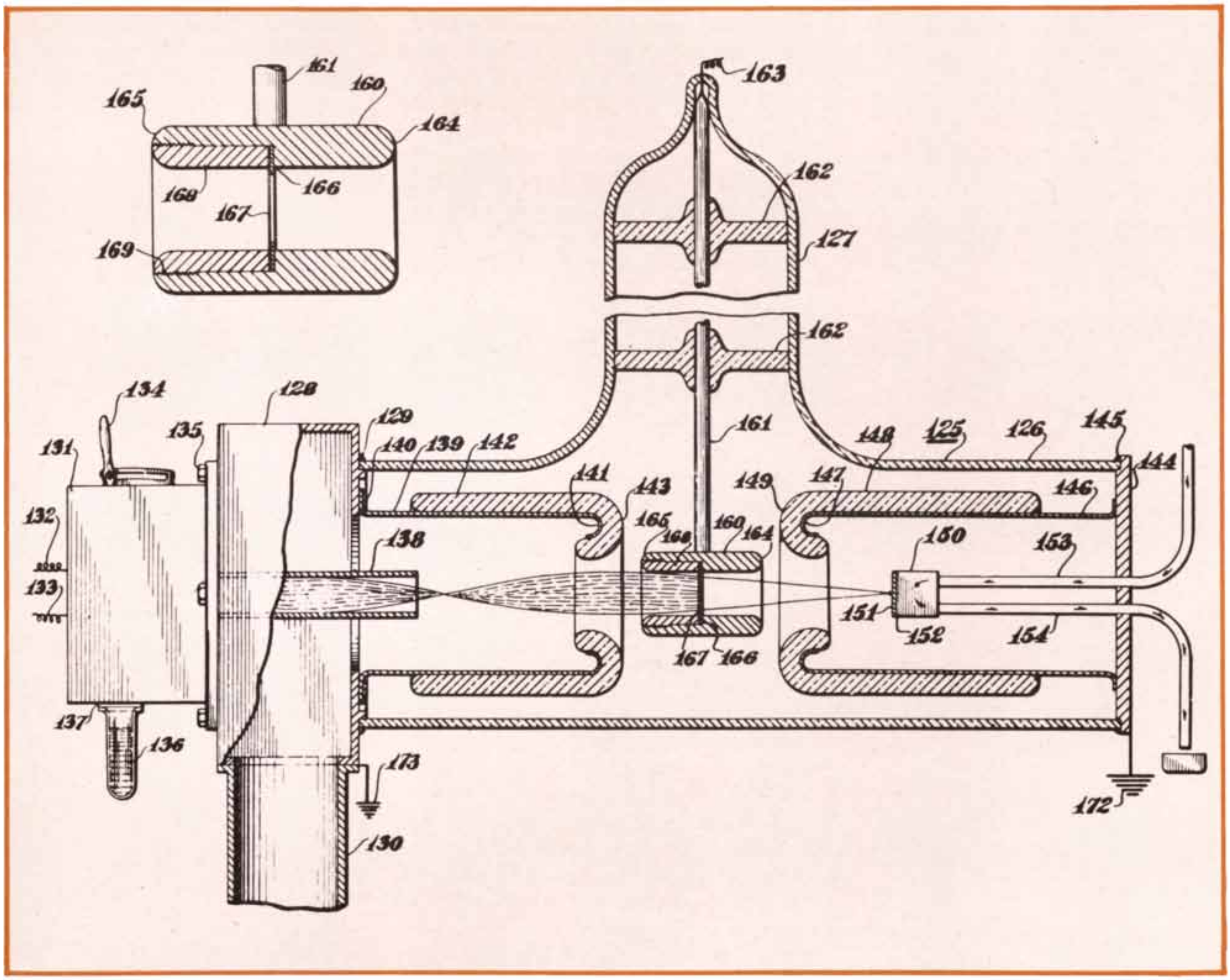
very thick slabs of steel, torpedoes and other equipment for the U.S. Navy. The maximum terminal voltage of these accelerators was limited not by the corona discharge and sparks of the older air-insulated machines but rather by the voltage capacity of the acceleration tubes. In the period immediately after the war, machine energies were increased at first simply by using longer and longer acceleration tubes, but it soon became clear that the increase in voltage was much less than a linear function of the increase in tube length, and the usable terminal voltage of pressurized accelerators "stuck" at about five million volts in spite of many efforts to do better.

Nuclear physics was of course immensely exciting at this period and the nucleus was proving more difficult to understand than had been expected. The more it was probed, the more it seemed to remain hidden. Higher energies were desired from d.c. machines because although work with cyclotrons was showing new and exciting information, the cyclotron lacked the energy resolution and energy variability needed to resolve the data.

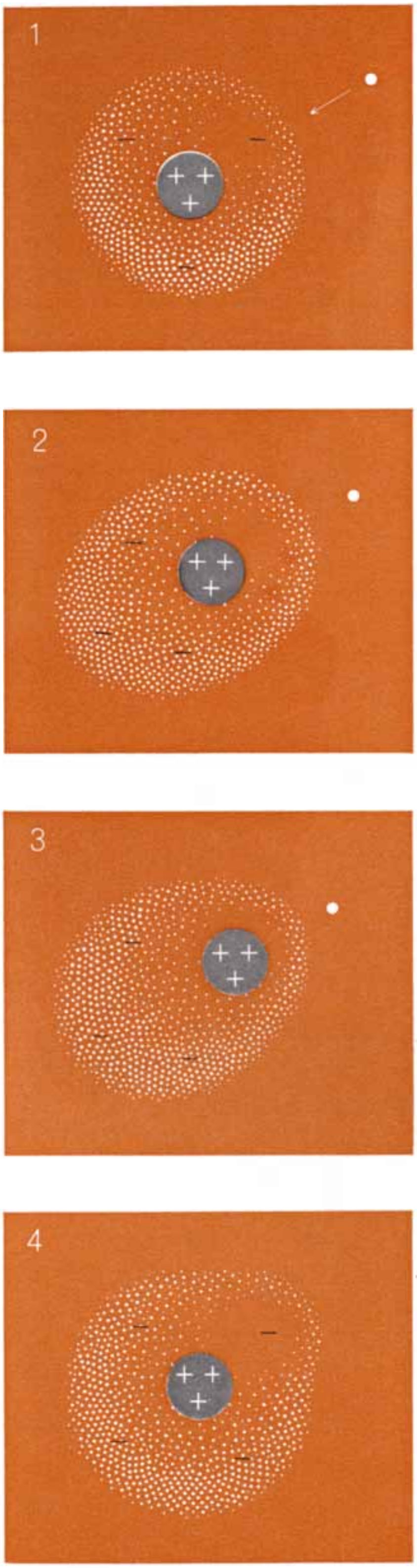
Aware of this problem but knowing nothing of Bennett's earlier work, Luis W. Alvarez built a small charge-changing accelerator at Berkeley in 1951 and with an improved negative-ion source showed that the charge-changing idea was eminently practical. Events now moved at a faster pace. A solution had been demonstrated and, as nuclear physicists were eager to obtain higher energies with the precision of the d.c. accelerator by any means, the conditions necessary to make a large charge-changing accelerator practical were coming into being. Then Herb developed a high-current negative-hydrogen-ion source much more intense than that used by Alvarez to demonstrate the feasibility of the charge-changing scheme. Van de Graaff, now becoming aware of the practicality of a high-energy, high-current accelerator with a performance exceeding that of any existing d.c. machine, persuaded the High Voltage Engineering Corporation, a company already building six-million-volt electrostatic accelerators and smaller belt generators, to build the first large negative-ion accelerator with charge-changing and voltage-doubling. By 1958 Van de Graaff, assisted by a team of engineers and physicists at High Voltage Engineering, had completed the development of a machine that became immensely successful; it is now part of the equipment of more than 45 university and government laboratories all over the world. It was this model that was christened the tandem accelerator; until this time the charge-changing accelerator had no generic name.

Like most such high-voltage accelerators, the insulating structure of the tandem Van de Graaff is built inside a pressure vessel containing a gas mixture (generally carbon dioxide and nitrogen at a pressure of 15 atmospheres). This mixture is a better insulator than air, and in any case the hazards of fire and explosion at high pressures preclude the use of a gas mixture containing free oxygen. The gas in the tank must be kept very dry because, as anyone knows who has watched the effect of bad weather on high-voltage transmission-line insulators, moisture severely reduces insulator performance. The voltage is generated by a belt, just as in the earlier machines, but because of the double acceleration process the terminal is a cylinder, open at both ends, instead of a spherical cap [*see illustration on next two pages*].

The horizontal layout of most tandem accelerators has contributed to their commercial success by making them inexpensive to install and easy to maintain. Although the first tandem accelerator was small compared with more recent models, the insulating column that supports the terminal represented a bold feat of engineering. The column is constructed of glass slabs bonded to metal planes, which serve to provide mechanical strength and to divide the total voltage into small parts. Because glass is weak and undependable when under tensile stress the column is placed under compression by means of a large spring and a mechanical linkage. In this way the column is made strong enough to carry loads of a ton or more. To distribute the voltage stress evenly the column is surrounded with "equipotential" rings with an outside diameter slightly less than that of the terminal, and the voltage is evenly divided by using a chain of precision resistors in series, each one connected to a column ring. Each ring is separated from its neighbors by a gap large enough to support the axial voltage gradient along the column easily but small enough to prevent radial field



EARLY PATENT for an accelerator that made use of the charge-changing, or tandem, principle to double the energy of a beam of particles was awarded to Willard H. Bennett of Ohio State University in 1937. In this copy of Bennett's original patent drawing a beam of negative ions (*dashes*) is accelerated to a terminal (*160*), where electrons are removed from the negative ions by collisions with a thin foil (*167*). The resulting positive ions are accelerated by the second gap and strike the target (*151*) with an energy corresponding to acceleration through an accelerator with twice the voltage. Bennett's proposal was apparently forgotten, and it was left to Luis W. Alvarez of the University of California at Berkeley to demonstrate the feasibility of the charge-changing idea in 1951.



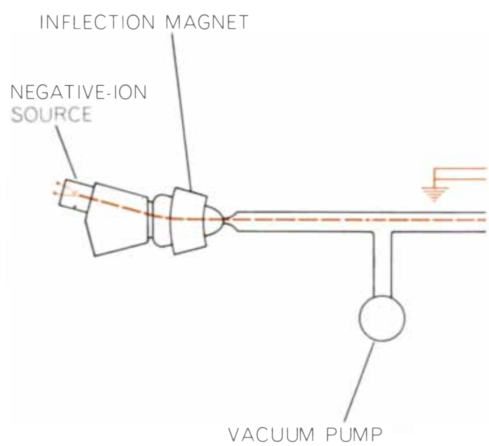
NEGATIVE ION is made by coupling an extra electron (*white dot*) to a neutral atom (in this case an atom of lithium). The polarization of the negatively charged electron cloud around the atom (*white stippling*) bares the positively charged nucleus (*gray*) and provides the necessary binding force.

concentrations that might initiate a spark to the tank wall. From an electrical viewpoint the terminal and column appear smooth, without projections or irregularities, and so make the best use of the insulating gap. The acceleration tube lies inside the column rings and is coupled to the column voltage by direct connection to each column plane. The accelerator tubes are made by sandwiching highly polished aluminum electrodes between glass insulating rings. Inside the tubes there is a vacuum; outside is the high-pressure insulating gas. The electrodes are not flat but are dished, rather like soup plates; they have a hole in the center to pass the ion beam. The dished electrodes protect the inner wall of the glass insulating rings from being struck by secondary particles generated by the beam.

Here is how the machine works. A beam of negative ions (say hydrogen ions) from the ion source is accelerated to a few tens of kilovolts and is injected into the entrance of the acceleration tube. Because the particles are charged and there is a strong field in the tube they are rapidly accelerated to the terminal, where they pass through a small-bore tube, or canal, fed at the center with a flow of gas. The negative hydrogen ions collide with the gas in this canal, and two electrons are removed from each ion, leaving a bare, positively charged hydrogen nucleus (a proton). The particle is not noticeably slowed down by losing the two electrons and enters the second acceleration tube with unchanged velocity; there, because its charge is now positive, it is accelerated out of the machine back to ground. The energy of a beam on leaving the tandem accelerator is consequently equal to the terminal potential times the number of electrons removed (plus a small addition to account for the injection energy). In practice the emergent beam contains some unwanted components, either because some ionized gas in the terminal is accidentally accelerated or because other negative ions are injected with the wanted beam. Fortunately the particles leaving the accelerator have different energies or masses and it is possible to separate the primary beam from its contaminants by means of a deflection magnet.

The deflection magnet serves a second useful function. It can be used to stabilize the accelerator and to measure the momentum or energy of the beam. Usually the beam is bent through 90 degrees, an angle that gives the magnet a high resolving power and useful focusing properties. The geometry of analysis is fixed by having the beam pass through a narrow entrance and a series of gaps or slits, which closely define the path of the beam through the magnet. Once the magnet has been calibrated by using known nuclear reactions, the magnetic-field setting determines the beam energy, provided that the mass and the charge of the analyzed ion are known. If, after initial adjustment, the accelerator voltage varies, the beam energy will also vary, and as a result the beam will strike one of the exit slits more strongly, giving a signal that can be used to control, or "fine-trim," the voltage of the accelerator.

The machine that has just been described in some detail is only one of a series of accelerators that could be constructed using the charge-changing properties of fast atoms. Some other possibilities are shown in the illustrations on pages 30 and 31. One important feature

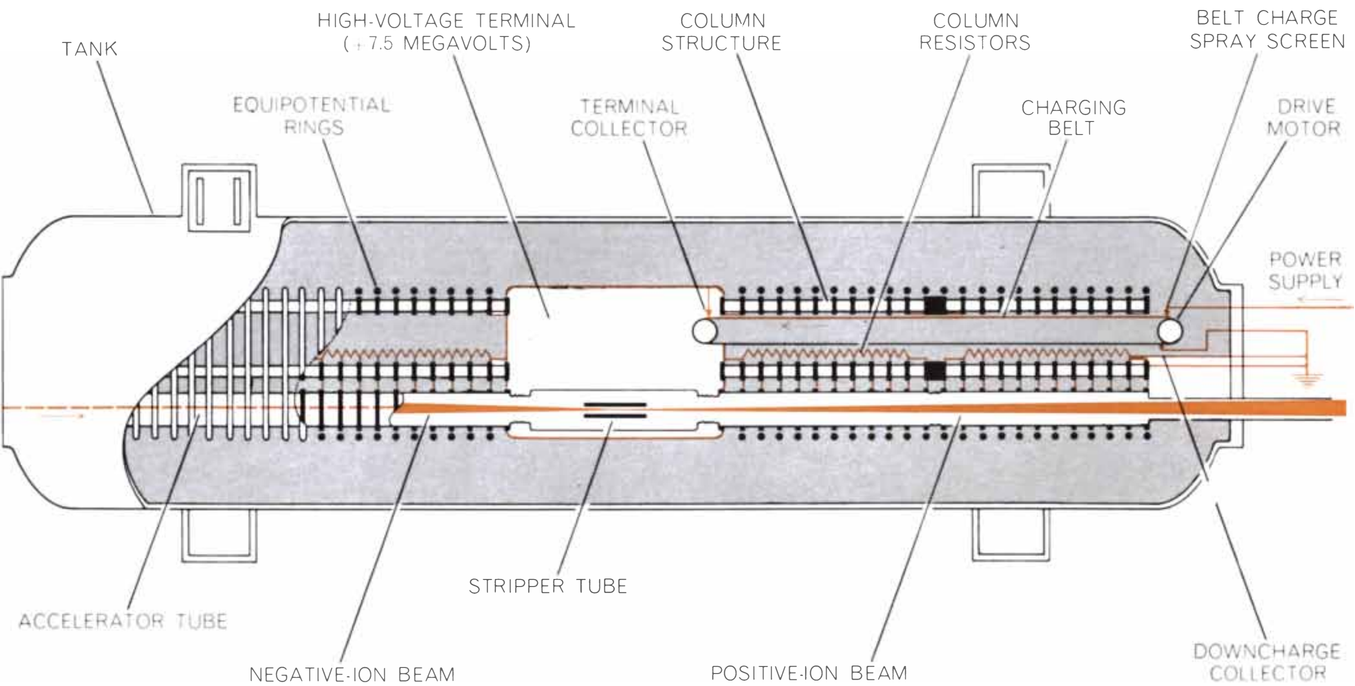


INNARDS of the first large negative-ion tandem accelerator, developed in 1958 by Van de Graaff and a group at High Voltage Engineering, are revealed in this cutaway drawing. The main components of the device are built inside a pressure vessel containing an insulating gas mixture. The voltage is generated by a belt, just as in the earlier machines, but because of the double acceleration process the terminal is a cylinder, open at both ends, instead of a spherical of all these machines is that charge conversion in the high-voltage terminal is almost 100 percent efficient. Positive-neutral operation would be restricted to quite low energies (less than a million electron volts) but could find application for such things as ion implantation in semiconductor fabrication. Neutral-negative operation is useful primarily for injection into another tandem to gain higher energies. Neutral-positive operation is the tandem way of accelerating ions of elements that cannot be made negative.

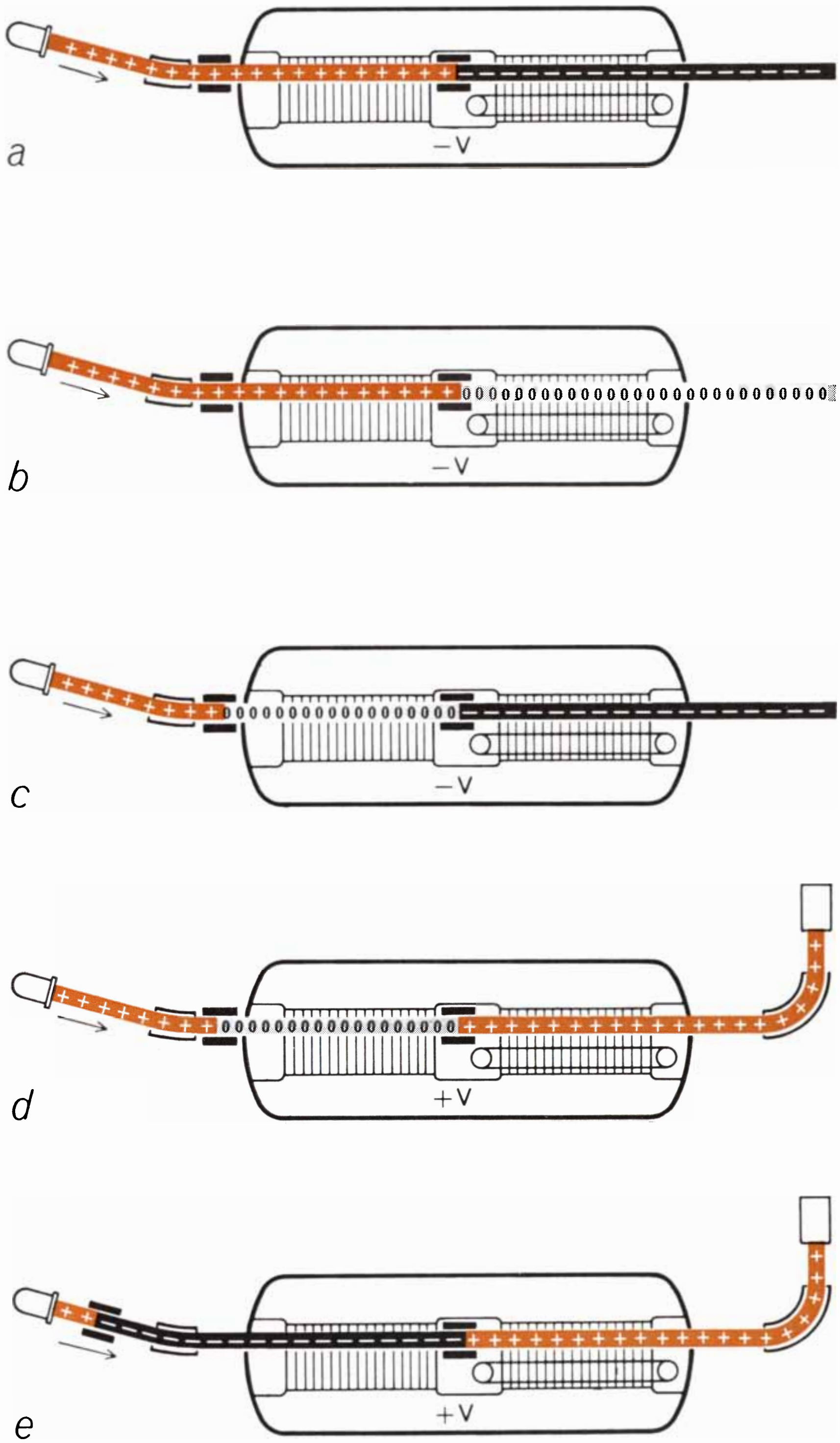
The initial difficulties inherent in developing negative-ion sources and the importance of energy multiplication obscured an important additional advantage of the tandem accelerator. Because the ion source is outside the accelerator's pressure vessel, it is accessible for adjustment or repair and very little time is wasted when the source malfunctions or needs a new part. Inside the pressure tank of the tandem accelerator there is no electronic circuitry that can be damaged by sparks, and as a result the tandem has turned out to be a most dependable device—on occasion operating around the clock, six or seven days a week, for a year without the necessity of opening the tank for repair.

Ion sources, on the other hand, remain, even after 40 years of development, one of the most unpredictable tools in physics. This is particularly true if ions of corrosive elements such as chlorine or oxygen are desired. The plasma of such an ion source is highly reactive with the materials used to build the source, and the lifetime of some parts, for example the incandescent filament, is often less than 40 hours. (The situation would be much worse were it not for the fact that most ion sources operate at pressures of less than a thousandth of an atmosphere.) In addition to this problem there is the occasional need to change ion species, say from hydrogen negative ions to oxygen negative ions. One way to make the change and to avoid delays is to have more than one ion source permanently attached to the system. Each ion source can then be switched into the accelerator by an inflection magnet. Thus the tandem accelerator can be regarded as the accelerating component at the center of a complex of ion-beam inflection and distribution systems. In spite of the obviousness of this concept, however, it was several years after the first tandem accelerator went into operation that it became routine to provide more than one ion source with the accelerator.

Higher energies were, and still are, more important to most researchers than the greater flexibility provided by a number of ion sources. The sudden increase in energy made possible by the first tandem did nothing to reduce the desire of nuclear physicists for still higher energies, and before the tandem was fairly in operation ways were being sought to reach new goals. Acceleration tubes capable of insulating more than six or seven million volts dependably did



cap. The insulating column that supports the terminal is constructed of glass slabs bonded to metal planes, which serve to provide mechanical strength and to divide the total voltage into small parts. The column is placed under compression by means of a large spring and a mechanical linkage. To distribute the voltage stress evenly the column is surrounded with "equipotential" rings; the voltage is evenly divided by using a chain of precision resistors (*zigzag lines*) in series, each one connected to a column ring. The acceleration tube lies inside the equipotential rings and is coupled to the column voltage by direct connection to each column plane. The acceleration tubes are made by sandwiching highly polished aluminum electrodes between glass insulating rings; each electrode has a hole in the center to pass the ion beam. The particles from the negative-ion source are injected into the entrance of the acceleration tube and are rapidly accelerated to the terminal, where they pass through a gas "stripper" tube, losing two or more electrons each and emerging as positive ions. The positive-ion beam is then accelerated out of the machine back to "ground" voltage. The energy of the emergent beam is equal to the terminal potential times the number of electrons removed plus a small addition to account for the injection energy. Variants of this basic machine are in use at more than 45 research laboratories all over the world.

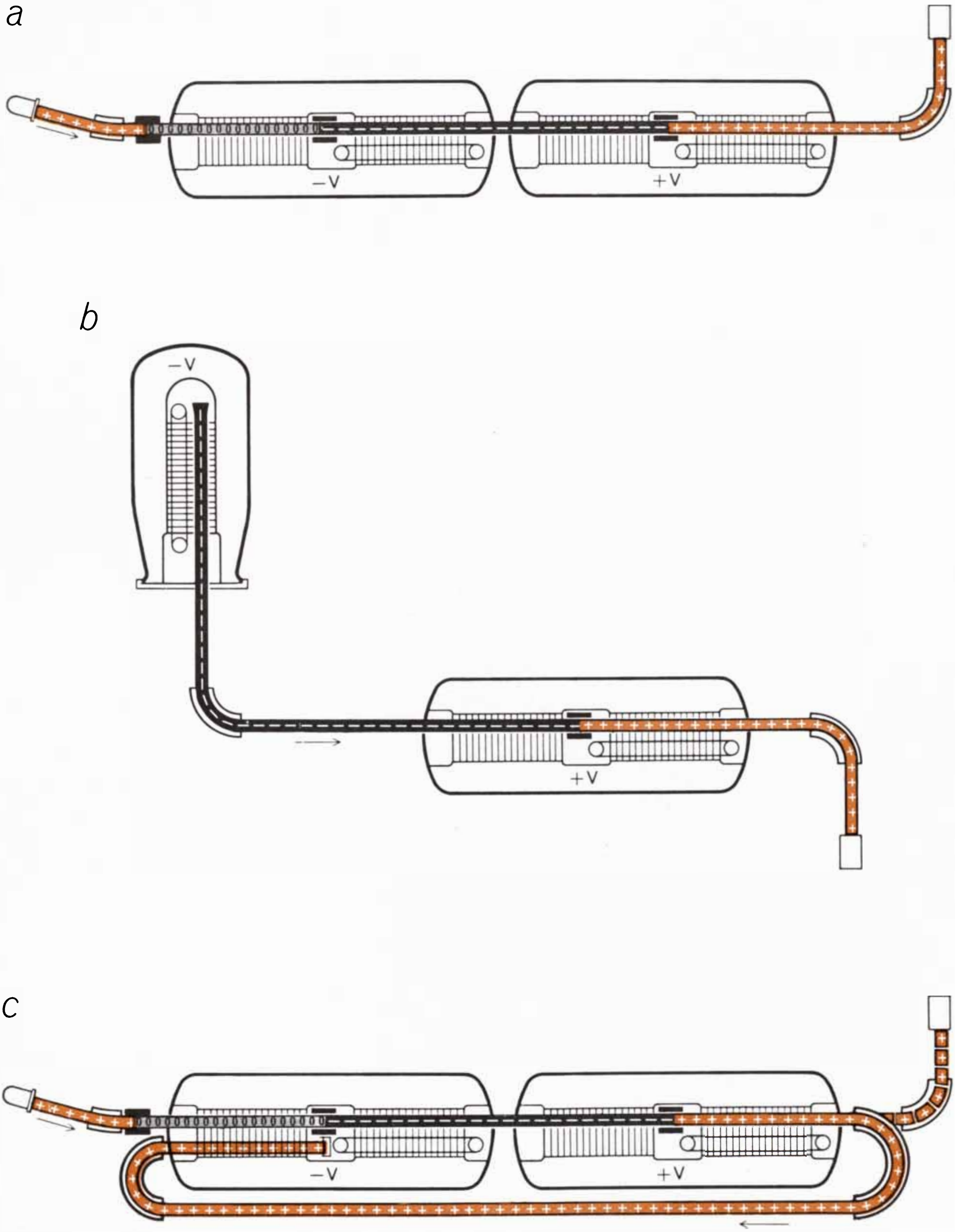


OTHER CHARGE-CHANGING SCHEMES used in tandem accelerators are represented here. The first three machines are designed specifically to produce a beam of particles for injection into a second accelerator. The positive-negative version of this design (*a*) is employed to obtain optimum yields of heavy negative ions. The positive-neutral arrangement (*b*) is used to obtain well-collimated and energetic beams of neutral particles. The neutral-negative accelerator (*c*) serves as an injector to a three-stage tandem. In the one-stage tandem (*d*) a beam of neutral particles generated outside the pressure vessel is "drifted" to the terminal of the accelerator, where they are converted into positive ions and accelerated out of the machine. In the two-stage tandem (*e*) the particles are accelerated twice, first as negative ions to the terminal, where they are stripped of two or more electrons, and then out of the machine to ground potential as positive ions. In all the machines the ion source is at ground, and electron attachment or loss is exploited to achieve the desired result.

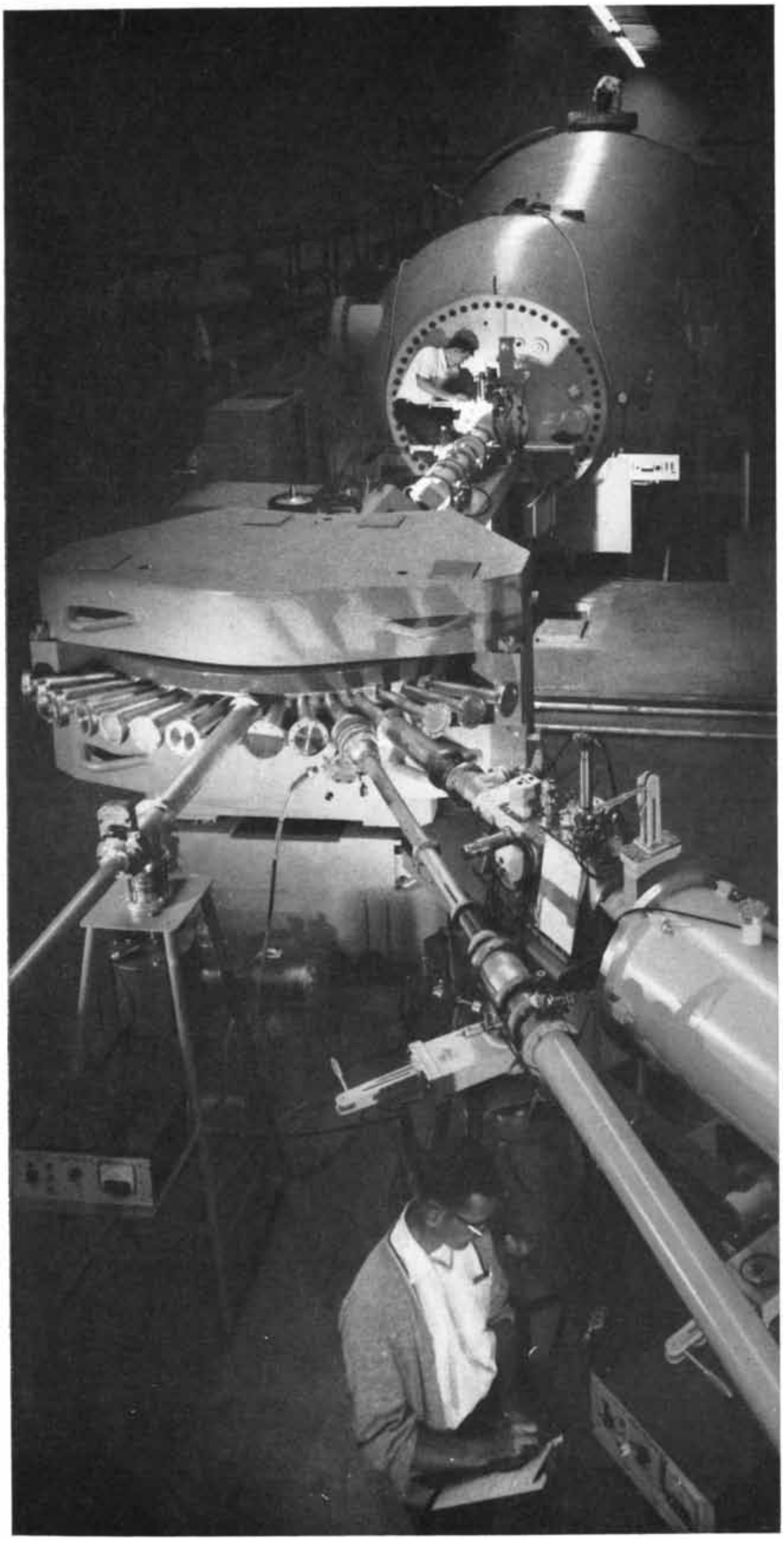
not exist in 1960. To reach higher energies than could be achieved with the first tandems, Van de Graaff proposed that two tandems be arranged in line so that the beam from one could be injected into the other. A special ion source injected an intense beam of neutral atoms into the first accelerator. Here a small fraction were converted into negative ions and were accelerated from the terminal of the first accelerator (which had to be at a negative potential) into and through the second accelerator, thereby reaching an energy about one and a half times the energy of a single machine. This ingenious method of obtaining higher energies proved to be extremely difficult to put into practice, and many scientific and technical obstacles were encountered before operational success was achieved.

While the development of the neutral injection tandem was proceeding Van de Graaff proposed a method for overcoming the total-voltage effect, the phenomenon that prevented a linear increase in voltage with tube length. The acceleration tube embodying Van de Graaff's new idea was called the inclined-field tube, and when tested it was found to give a linear increase in voltage with tube length. This one invention removed the major risks attending the construction of accelerators with voltages higher than six or seven million volts. The tube is constructed with groups of electrodes inclined first one way with respect to the axis and then the opposite way in a manner allowing the energetic primary-beam particles to pass through the accelerator with very little deviation. Slow secondary particles created by the beam in the residual gas of the tubes are swept into the electrodes before they can gain enough energy to produce effects leading to voltage breakdown. Acceleration tubes could now be increased in length whenever a higher voltage across them was required.

Since the time of this invention tandem accelerators have been built with higher and higher voltage capacities, culminating in one recently constructed that has reached a terminal voltage above 21 million electron volts [*see illustration on page* 25]. The volume of the pressure tank of this machine is 20 times greater than that of the original tandem. This powerful new accelerator will extend the number of the nuclear reactions that can be studied. So far protons and alpha particles have been the projectiles most commonly employed. There have been two reasons for this: first, voltages high enough to accelerate heavy ions so



THREE MULTISTAGE DESIGNS are among the possibilities for increasing the energy of the beam from a tandem accelerator. The three-stage tandem (*a*) is a combination of an injector tandem and a two-stage tandem. The combination could be built in two separate pressure vessels as shown here or in one long pressure vessel. In an alternative version of this design (*b*) the negative-ion source is located inside the terminal of the first accelerator. In the four-stage tandem (*c*) the positive ions are stripped of additional electrons after emerging from the second accelerator and are therefore at a higher charge state before undergoing the fourth acceleration. A serious disadvantage of this combination is that the final target is inside a high-voltage terminal and therefore is less accessible.



SWITCHING MAGNET (*foreground*) **can deflect the output beam of a tandem accelerator into various pieces of experimental equipment. The machine in the background is the same as the one in the background of the photograph on page 25. When this photograph was made, it was employed alone to accelerate heavy ions for use in a study of nuclear structure.**

that they could overcome the electrostatic forces between them and collide with each other were not available, and second, nuclear reactions are difficult enough to understand without introducing complicated many-bodied projectiles.

The availability of much heavier ions with sufficient energy to produce nuclear reactions, however, introduces an important new class of phenomena for consideration. It becomes possible to study processes that are the inverse of nuclear fission in the sense that nuclear particles can be added to certain heavy nuclei instead of being removed from them. Some 400 new isotopes have been produced artificially in this way, and it is estimated that more than 10 times as many can be discovered if the right projectile and target nuclei can be brought together. Some of these new isotopes may have useful properties. In addition there is the exciting possibility that new stable elements can be created if the right conditions are found. Now that very high voltages are becoming available, the tandem is an invaluable tool for finding the correct nuclear reaction because it has greater energy variability and precision than any other type of accelerator.

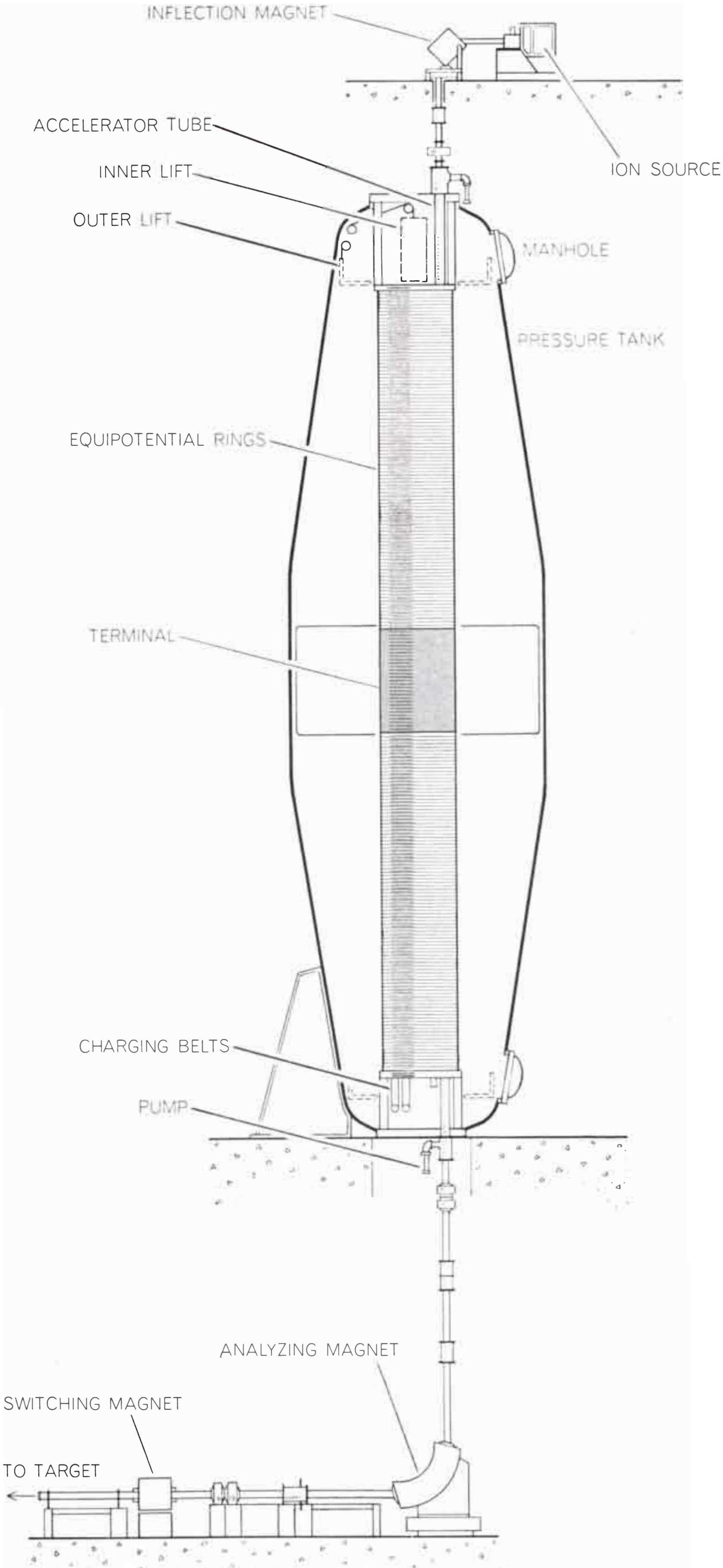
The energy with which heavy ions can be obtained from a tandem accelerator depends on the number of electrons that can be removed in the terminal. Negative hydrogen has only two electrons and both can be removed at very low energies in a target. Negative helium has three electrons and, because the innermost electron is bound more tightly to the nucleus, a higher-energy collision is needed to remove this last electron. To strip oxygen completely an energy above 30 million electron volts is required, and heavier ions such as negative iodine (which has 54 electrons) would need voltages of many hundreds of megavolts to remove all the electrons.

Fortunately, by taking advantage of another technique suggested by Van de Graaff, enough electrons can be removed at available or projected tandem terminal potentials to provide energies high enough to allow nuclear reactions to take place. The ions are stripped not only in the terminal but also halfway down the positive acceleration column, where, because they are at a much higher energy, they can be stripped to a higher charge state and consequently accelerated to a higher energy. It can be calculated that with this technique and a single 20-megavolt terminal tandem, iodine ions of more than 700 megavolts can be obtained, an energy high enough to overcome the repulsive force between iodine and uranium and to bring these two nuclei together.

The results of recent studies by our group at High Voltage Engineering show that a small fraction (about one out of every 10 million) of certain ions such as bromine and iodine that are stripped in the terminal lose more than 20 electrons each. A small number of positive iodine-26 ions have, in fact, been observed at a stripping energy of 14 megavolts. From the energy dependence of these results it appears that a 20-megavolt tandem with a single gas stripper could deliver a beam of molybdenum ions with sufficient energy to investigate a possible nuclear reaction in which the molybdenum ions collide with plutonium-94 atoms to produce a new element, No. 114 in the periodic table, along with the by-products gallium 20 and helium 2. The species created by such a reaction would be by far the heaviest atom found to date and would be in the middle of what is expected to be an island of element stability.

Many other reactions are possible by which such "superheavy" elements can be investigated, and higher terminal potentials would make the tandem accelerator a unique instrument for this purpose. The energy homogeneity of the beam from the accelerator and the ease with which the energy can be varied make it a perfect tool for unraveling the complicated secrets of the nucleus. Accordingly a large vertical tandem has recently been proposed with a designed voltage of 30 megavolts, which would be a significant advance over the 21 megavolts already achieved and very important to the field of heavy-ion research [*see illustration at right*].

Using a single tandem accelerator, still higher voltages would be needed to bring two uranium nuclei together, the ultimate objective in the view of many nuclear researchers and certainly the most difficult. Judging from recent progress the tandem accelerator is not many years away from becoming a universal accelerator in the sense that a complete choice of projectile and target will be available for such nuclear experiments.



LARGE VERTICAL TANDEM at right has been proposed for heavy-ion research. With a designed voltage of 30 megavolts, this accelerator would represent a significant advance over the 21 megavolts that has already been achieved. The pressure tank would be 128 feet long and would have an inside diameter of 35 feet in the terminal region.

The Structure and Function of Antibodies

The complete amino acid sequence of an immunoglobulin molecule has been determined, defining the structure of antibodies and providing information on their evolution and differentiation and how they work

by Gerald M. Edelman

"Immunity" is an everyday word, ordinarily applied to the elaborate set of responses by which the body defends itself against invading microorganisms or foreign tissues. There is much more to immunity than its clinical aspects, however. What we have come to know about the immune system and its key molecules, antibodies, makes it apparent that immunology bears directly on some very fundamental problems: the nature of the mechanisms whereby molecules recognize one another, the manner in which genes are expressed in higher organisms and the origin of a variety of disease states, including cancer. In one way or another the solution of these deep problems will require an understanding of the structure of antibody molecules.

Antibodies have been known since the classic studies of Emil von Behring in the late 19th century. Only recently, however, have we begun to understand how vertebrate organisms recognize the sometimes subtle chemical differences between their own molecules and foreign molecules, which are termed antigens. Our insights rest on three serial developments. The first was the demonstration by Karl Landsteiner in 1917 that animals could form antibodies against certain small organic chemicals of known structure. By manipulating and modifying these "haptens," Landsteiner and others showed that antibodies distinguish among different antigens by recognizing differences in their shape. Moreover, the early studies implied that the number of different antibodies any single animal can make must be very large indeed. If an animal could make antibodies that could specifically bind a synthetic hapten the animal or its ancestors had never encountered before in nature, it seemed likely that the animal could make antibodies to almost any foreign antigen. Further work has largely supported this inference: most vertebrates are indeed capable of making many thousands of different antibodies. The second fundamental development was the bold idea of selective immunity advanced in the late 1950's by Niels K. Jerne and Sir Macfarlane Burnet, who proposed that the body already has all the information for making any of its antibodies *before* it ever encounters an antigen. The third development was the analysis of the structure of antibodies, which has taken place largely in the past decade. Before discussing this last development in detail, it will be useful to outline the seminal idea of selective immunity and some of the advances made by cellular immunologists.

The main notion, as implied above, is that the cells of the antibody-forming system have among them all the information they need to make any antibody molecule before they ever encounter any antigen. The antigen molecule does not instruct antibody-producing cells to shape the antibody molecule to fit it. Instead it selects cells that are already making antibodies that happen to fit. Then it stimulates those cells to make large quantities of the antibodies.

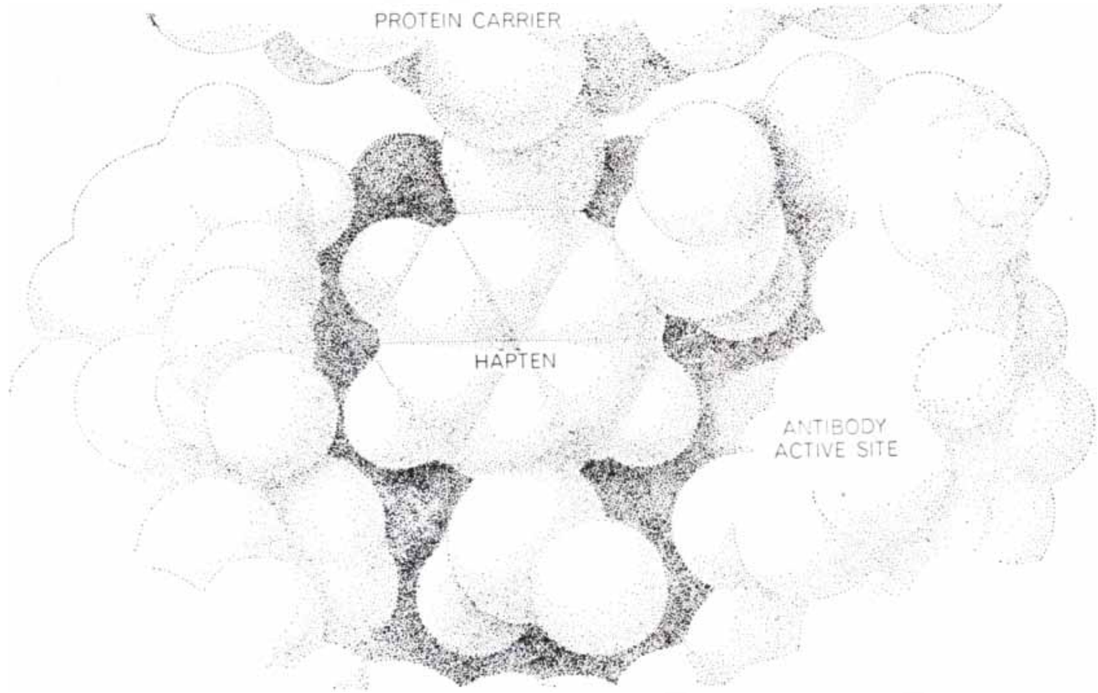
Antibodies can be likened to ready-made suits. The antigen is a buyer who decides to pick a number of different suits that fit more or less well rather than instruct a tailor to make one suit to fit him to order. To be well satisfied, the buyer must patronize a store with a very large stock of suits in a great variety of sizes and styles. The immune system is like a store with an almost unlimited stock, one ready to please any possible customer. This analogy fails in one important respect: to be complete it should provide that after each somewhat different ready-made suit is picked the manufacturer would proceed to make thousands of exact copies of it.

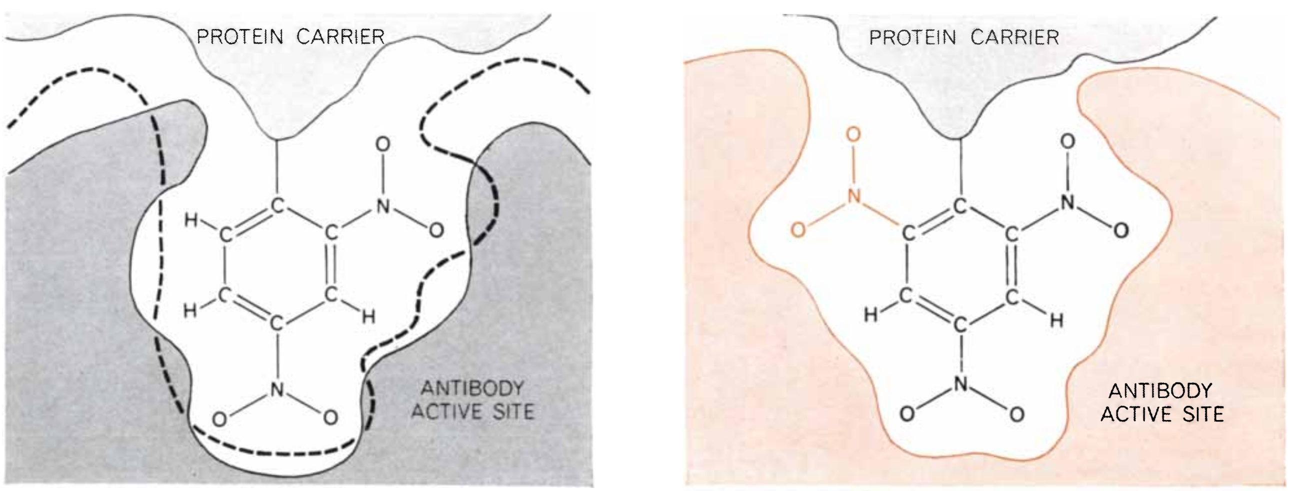
In a simplified picture of the cellular mechanisms corresponding to this selective response, each cell makes only one kind of antibody, which has an antigen-binding site of a particular shape [*see top illustration on page 36*]. Presumably that antibody is located at the cell surface. An antigen injected into the body "tries on" different shapes. If a particular antibody "fits" more or less well, the cell making it divides and matures. Its progeny then make many more copies of the identical kinds of antibody, which may then be released into the blood to carry out their function of defense or of tissue rejection. Notice that this is a form of molecular recognition machine and that the specificity of recognition rests both on the presentation of a variety of antibodies and on the capacity of the cells to "amplify" the results of a recognition event. How are these requirements accomplished at a molecular level? In order to answer that question satisfactorily we must know a good deal about the structure of the antibody molecule itself.

A decade ago a number of experimental observations began to shed light on the details of antibody structure. The advance came when the results of sophisticated protein chemistry and genetic analysis fitted together with a classical observation about the products of a certain cancer. At the Rockefeller Institute in 1959 I found that antibody molecules consisted of polypeptide chains, or protein subunits, of more than one kind, and that the chains could be separated from one another by chemical means and studied in detail. These chains were called light chains and heavy chains because of the difference in their size, or molecular weight. At the same time R. R. Porter, now at the University of Oxford, showed that the antibody molecule could be cut into three different pieces by enzymes that cleave polypeptide chains. Two of them, termed "fragment antigen binding" (F*ab*), were identical and would still combine with antigen. The third, "fragment crystalline" (F*c*), was quite different: it would not combine with antigen but could be crystallized readily [see "The Structure of Antibodies," by R. R. Porter; SCIENTIFIC AMERICAN, October, 1967]. The observations on the two polypeptide chains and on the two fragments were the starting point for a series of investigations in many laboratories into the details of antibody structure.

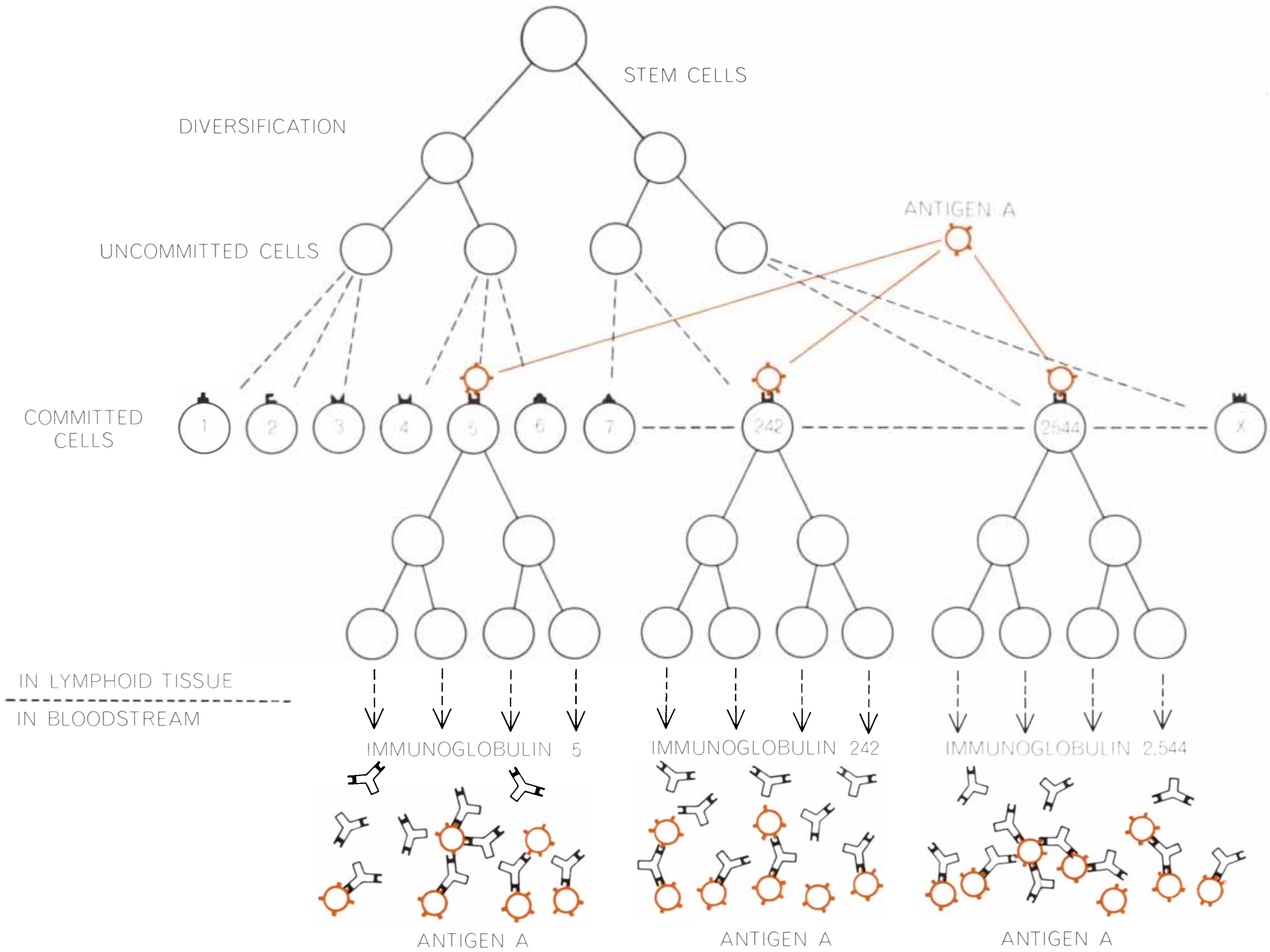
Antibodies, it was known, were a family of proteins with a number of properties in common, found in the gamma globulin fraction of the blood. Unlike all proteins whose structure had been determined, antibody molecules were known to be very "heterogeneous": no single sequence of amino acids—the building blocks of proteins—could represent the polypeptide chains of antibodies, as can be done, for example, in the case of a "homogeneous" protein such as insulin or hemoglobin. This fact, together with the large size of antibody molecules, made it infeasible to carry out detailed chemical analyses of such molecules or to determine exactly how antibodies that bound to different antigens differed from one another. Fortunately the structural studies of the polypeptide chains of the immunoglobulin molecule led to a clue that made it possible to bypass the problem raised by the intrinsic heterogeneity of antibodies. The clue had to do with the nature of certain homogeneous proteins made by tumors of plasma cells, the cells that ordinarily produce the most antibodies.

Knowledge of these tumors goes back to 1847, when Henry Bence Jones, physician at St. George's Hospital in London, published a paper titled "On a new substance occurring in the Urine of a patient with Mollities Ossium." It





ANTIBODY recognizes a specific antigen by its fit. The top drawing shows the fit between the combining site on an antibody and a "hapten" antigen, a dinitrophenyl group, on a protein carrier. The bottom drawings show that two different antibody contours (*gray shape and black line*) can fit the dinitrophenyl group, one better than the other (*left*). If a third nitro group (*color*) were on the hapten (*right*), those two antibodies would not fit; a third antibody with a different antigen-combining site (*color*) would fit this picryl antigen. Because of picryl's similarity to dinitrophenyl, the third antibody would also fit the original hapten, but less precisely.

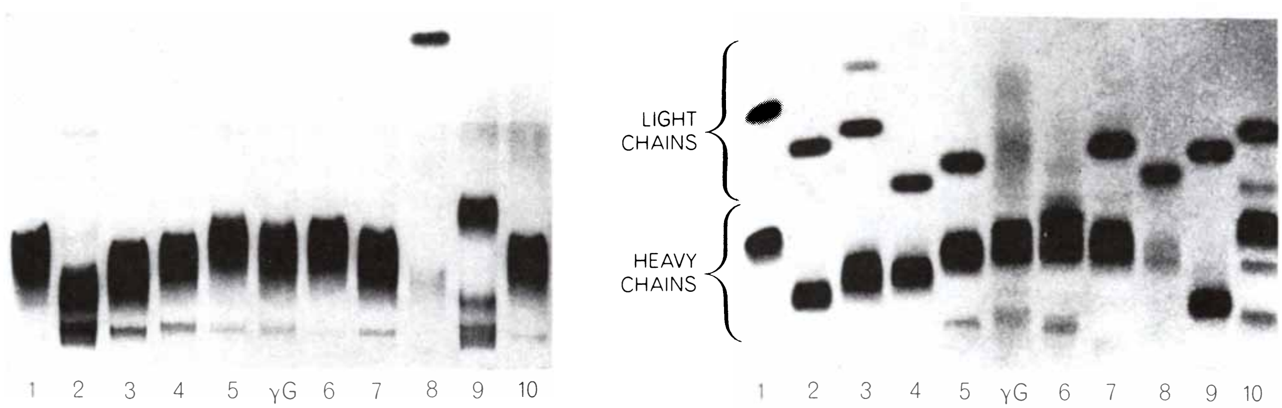


SELECTIVE-IMMUNITY THEORY holds that stem cells (precursors of antibody-producing cells) contain information for making all possible antibodies; at some point in embryonic development each is committed to producing a unique immunoglobulin (*numbers*). These receptor antibodies can interact with various antigens. A single antigen (*color*) may be recognized by more than one antibody-producing cell. Interaction of an antigen with a cell stimulates proliferation of the cell and the synthesis of antibody.

began as follows: "On the 1st of November 1845 I received from Dr. Watson the following note, with a test tube containing a thick, yellow, semi-solid substance:—'The tube contains urine of very high specific gravity; when boiled it becomes highly opake; on the addition of nitric acid it effervesces, assumes a reddish hue, becomes quite clear, but, as it cools, assumes the consistence and appearance which you see: heat reliquifies it. What is it?' "

Jones verified the peculiar thermosolubility properties of the protein, subjected it to a careful elementary analysis and concluded that it was the "hydrated deutoxide of albumin."

In succeeding years many attempts were made to answer Dr. Watson's question in a definitive way, but although some 700 papers on the subject appeared



MYELOMA PROTEINS from different patients are compared with a normal human immunoglobulin fraction by electrophoresis on a starch gel. The intact immunoglobulins migrate in approximately the same way (*left*). After dissociation into light and heavy chains (*right*) the myeloma proteins show sharp bands in the light-chain position but the normal protein shows a diffuse zone there because it is a heterogeneous mixture of immunoglobulins. Protein No. 8 is a Bence Jones protein and it therefore shows no heavy chain.

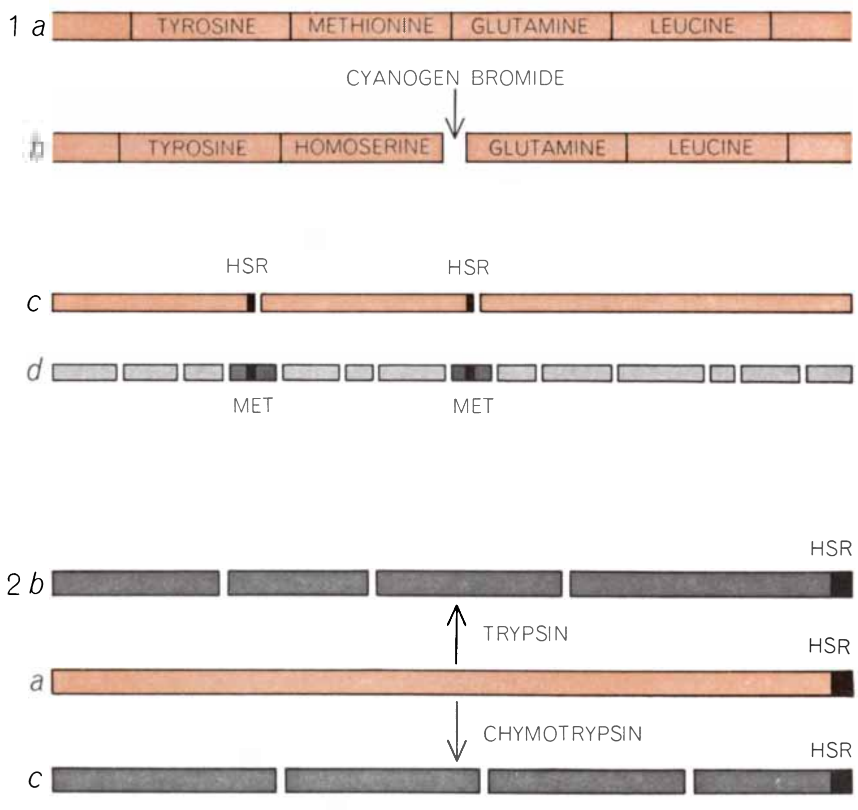
in the ensuing century, Bence Jones proteins remained a kind of medical and biochemical curiosity except in the domain of practical diagnosis: the demonstration of the protein in the urine called for a diagnosis of multiple myeloma, the malignant disease of plasma cells that was formerly called mollities ossium. This disease is usually associated with malignant proliferation of plasma cells, excessive production of serum gamma globulins called myeloma proteins, bone lesions, disturbances of calcium metabolism, kidney disorders and often, of course, excretion of the characteristic Bence Jones proteins.

It seemed that these proteins had something to do with immunoglobulins, but the exact relation remained obscure. The 1959 finding that immunoglobulins contained multiple polypeptide chains [*see bottom illustration on opposite page*] suggested that Bence Jones proteins were homogeneous light chains of the myeloma protein made by the tumor but not incorporated into whole molecules. This hypothesis was confirmed by my student Joseph A. Gally and me in 1962. Because different Bence Jones proteins had different amino acid compositions, we compared their properties with those of light chains of antibodies. These comparisons were instrumental in suggesting that antibodies with different antigen specificities differ from one another in the sequence of amino acids of which they are composed. Moreover, because the light chains produced by the myeloma tumors were pure, available in large amounts and smaller than a whole immunoglobulin molecule, it became possible to study the details of their chemical structure.

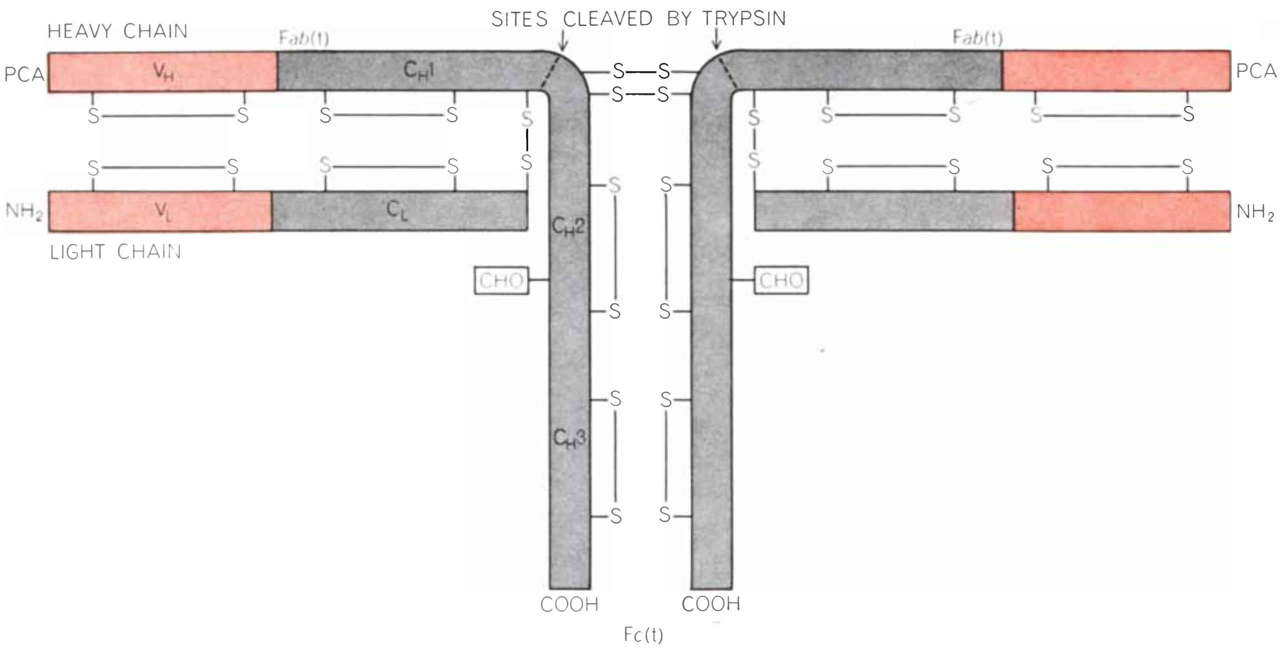
Once it had become apparent that these proteins might provide a clue to the nature of antibody variability, a number of laboratories undertook the task of determining their exact amino acid sequence. Since no two individuals produce the same Bence Jones proteins, each laboratory reported a different sequence, but from the first report of partial sequences by Norbert G. D. Hilschmann and Lyman C. Craig at Rockefeller University in 1965 it became clear that these proteins had a singular structure. Each molecule contained about 214 amino acids, linked together in a polypeptide chain. (The amino acids are numbered starting from the end of the molecule that is made first, the amino terminus.) From position 109 on various Bence Jones proteins had essentially the same sequence, and accordingly this part of the molecule was called the constant region. In striking contrast, the sequence of the first 108 amino acids differed markedly from one Bence Jones protein to another, and this first part of the chain was designated the variable region. Concurrent studies in several laboratories suggested that the heavy chains of myeloma proteins also had variable and constant regions. The homogeneity of the constant region enabled Robert L. Hill and his associates at Duke University to determine the amino acid sequence of the F*c* fragment of rabbit immunoglobulin.

It was against this background that my colleagues and I decided to attempt the determination of the complete amino acid sequence of a whole immunoglobulin molecule. The earlier structural studies had suggested an overall picture and we wanted to confirm and extend it in detail so that we could apply it to an analysis of the origin and function of antibodies. We obtained a large amount of plasma from a patient with multiple myeloma, because it was essential to have enough of at least one myeloma protein. As a matter of fact, we obtained two different proteins from different patients for purposes of comparison. The difficulties of our project were related to the enormous size of the molecule, which has 19,996 atoms and is larger in terms of the number of unique amino acid sequences than any protein that had been determined up to that time. Our approach was based on the pioneering methods first developed by Frederick Sanger to analyze the insulin molecule, and the challenge, successfully met last year, was whether these methods would suffice.

The immunoglobulin molecule is about 25 times as large as insulin. If we could break the immunoglobulin molecule, its chains and its fragments into small pieces about the size of the insulin molecule itself, then we could use standard methods for determining amino acid sequence. A useful tool for such protein surgery had already been devised by Erhard Gross and Bernhard



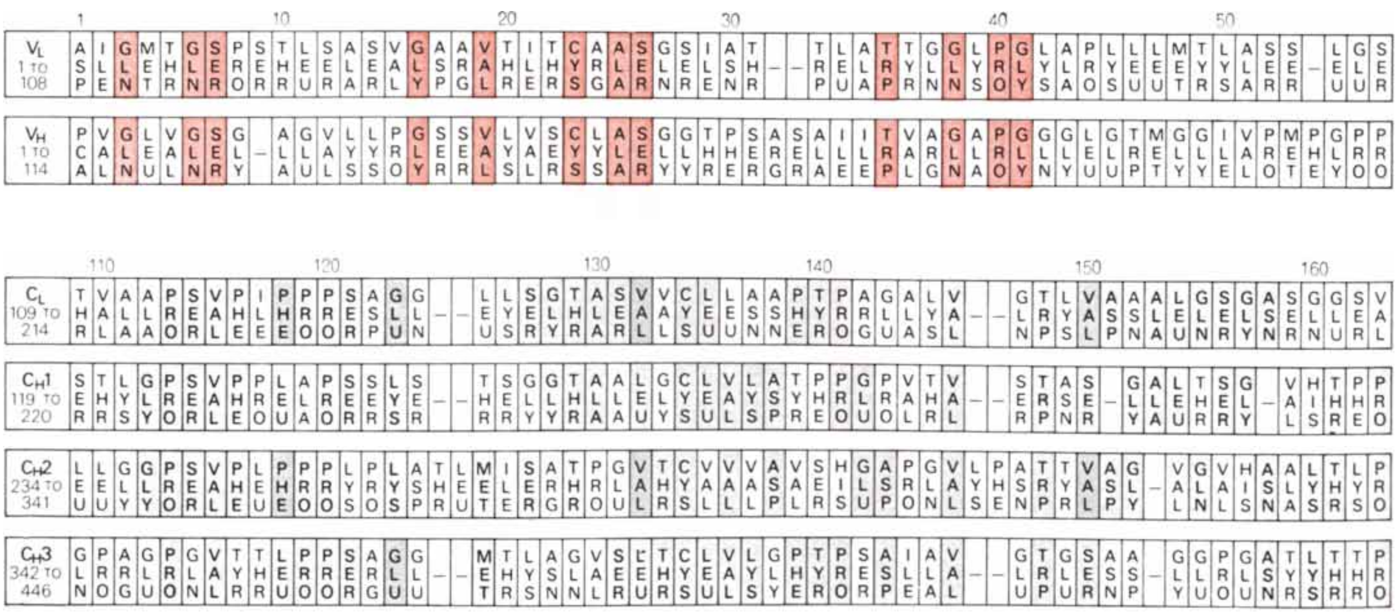
ANTIBODY CHAIN is cleaved by cyanogen bromide (CNBr) and the resulting fragments are ordered (*1*). The CNBr breaks a chain (*a*) at methionyl residues, which are converted into homoserine (*b*). To order CNBr fragments (*c*) the original chain is cleaved also with the enzyme trypsin, the tryptic fragments containing methionine are isolated (*d*) and their sequences are compared with those of the ends of the CNBr fragments. Then the amino acid sequence of each CNBr fragment must be determined (*2*). This is done by cleaving a CNBr fragment (*a*) with trypsin and determining the sequence of each tryptic peptide (*b*) by a chemical procedure. The tryptic peptides are ordered by comparison with the composition and partial sequences of different peptides (*c*) made by cleaving with chymotrypsin.



STRUCTURE of the immunoglobulin determined by the author and his colleagues shows two kinds of chain and regions in each. The protein can be cleaved into two antibody-binding fragments, F*ab*(t), and a "crystallizable" fragment, F*c*(t). Sulfur-sulfur bonds are designated —*S—S*—. Light chains have variable and constant regions (V_L *and* C_L). Heavy chains have a variable region (V_H) and a constant region divisible into three homology regions (C_H1, C_H2 *and* C_H3). *CHO* indicates carbohydrate. Chains have amino (NH_2), carboxyl (*COOH*) and pyrollidonecarboxylic acid (*PCA*) ends. V_H and V_L are homologous, as are C_L, C_H1, C_H2 and C_H3.

Witkop of the National Institutes of Health. It depended on cyanogen bromide, a reagent that selectively cleaves polypeptide chains at the positions occupied by the sulfur-containing amino acid methionine; because there were just a small number of methionines in the molecule, we could expect a decently small number of pieces. With this reagent we were able to cleave the heavy chain of the immunoglobulin into seven pieces and the light chain into three pieces [*see illustration on preceding page*]. Each piece was then separated from the others by chromatography. A key procedure in these separations was molecular sieving on Sephadex, a technique developed largely by Jerker O. Porath of the University of Uppsala, which speeded up the thousands of separations required to determine the structure of immunoglobulin.

After the fractionation of the pieces the next step was to establish their order.



AMINO ACID SEQUENCES of the variable regions (*top*) and of the constant homology regions (*bottom*) were fully determined. The extent of the homology between the two variable regions and among the four constant homology regions is indicated by the

This was done by cleaving the original chains not with cyanogen bromide but with enzymes that attack polypeptides at other specific sites. Those peptides that contained methionine and that would therefore overlap the cyanogen bromide fragments were then isolated. By comparing the two kinds of fragment we could see which ends of the cyanogen bromide fragments butted up against one another.

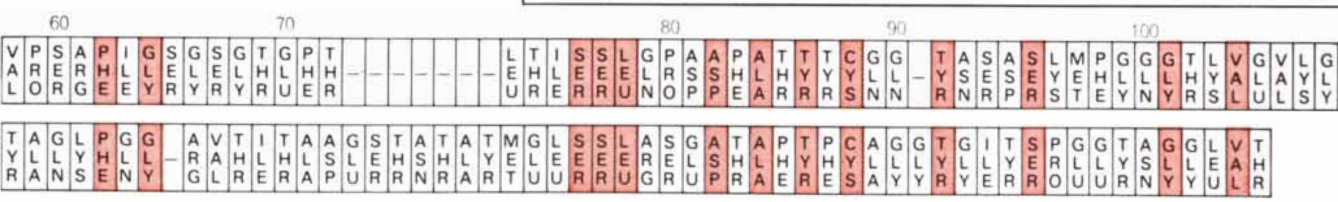
Each separate cyanogen bromide fragment could now be studied independently as if it were a separate small protein or polypeptide. Accordingly it was cleaved with enzymes into smaller peptides, which were separated. When small pure peptides were obtained, the sequence of their amino acids was determined directly by a chemical procedure. The order of the peptides was then established by breaking the whole cyanogen bromide fragment with a second enzyme that cleaved it at different sites and isolating a second set of peptides that overlapped the first set.

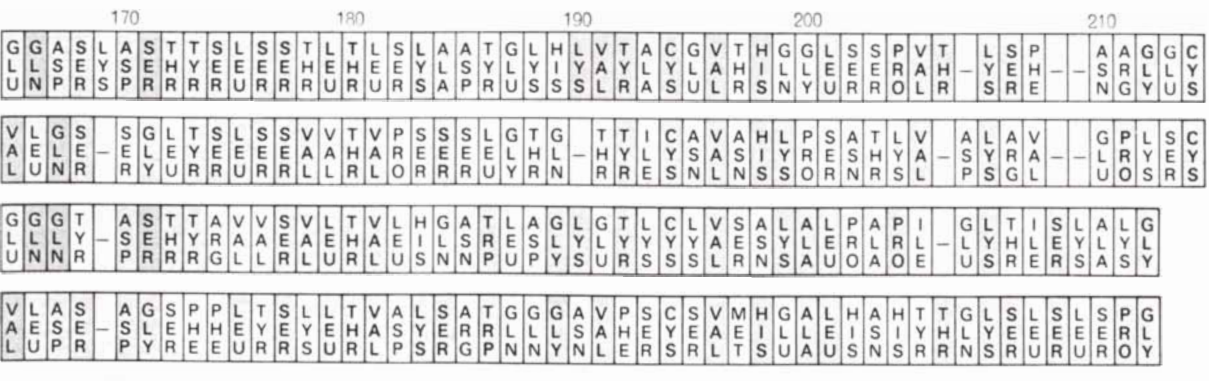
The sequence determination was thus a "two pass" procedure. In the first pass we obtained cyanogen bromide fragments and ordered them. In the second we treated each fragment as a separate protein, obtaining its peptides, ordering them and determining their amino acid sequence. When these tasks were finished, there remained the job of determining the location of the bonds between the sulfur atoms of the amino acid cysteine that helped to link the chains and parts of the chains together.

The completed structure showed that the antibody molecule differed from proteins that had been analyzed earlier not only in size but also in more unusual ways. Our molecule was what is classified as a γG, or gamma G, immunoglobulin molecule, an example of the most prevalent class of immunoglobulins. As earlier studies had suggested, such a molecule consists of two identical light and two identical heavy chains [*see top illustration on opposite page*]. The structure is symmetrical, each half consisting of one light and one heavy chain. Although the actual shape or three-dimensional structure of the chains is not known, it is established that they are held together by weak forces and by interchain sulfur-sulfur bonds between corresponding pairs of cysteines; similar intrachain bonds are formed within each chain at approximately equal intervals. The most striking feature of the structure is its division into two kinds of region, variable regions and constant regions, whose disposition is related to these intervals. The length of the variable regions was determined by comparing the amino acid sequences of the light and the heavy chains to the sequences of Bence Jones proteins and to the sequence of another heavy chain that was analyzed concurrently. As in the Bence Jones proteins, the regions are so named because in different antibodies the variable regions differ in the sequence of amino acids that make up the chain, whereas the constant regions have the same sequence in each of the major classes of antibodies (except for a single variable amino acid at position 191). It has now been firmly established that it is the different sequences in the variable regions that give different shapes to various antigen-binding sites. The variety of shapes provides for a range of specific interactions with a great variety of antigens, including small molecules, other proteins, carbohydrates and even DNA itself.

There is another feature of the structure that merits notice. Detailed examination of the constant regions showed evidence of internal periodicity, which had already been hinted at by the distribution of the sulfur-sulfur bonds. Por-

ALA	ALANINE	LEU	LEUCINE
ARG	ARGININE	LYS	LYSINE
ASN	ASPARAGINE	MET	METHIONINE
ASP	ASPARTIC ACID	PCA	PYROLLIDONECARBOXYLIC ACID
CYS	CYSTEINE	PHE	PHENYLALANINE
GLN	GLUTAMINE	PRO	PROLINE
GLU	GLUTAMIC ACID	SER	SERINE
GLY	GLYCINE	THR	THREONINE
HIS	HISTIDINE	TRP	TRYPTOPHAN
ILE	ISOLEUCINE	TYR	TYROSINE
		VAL	VALINE





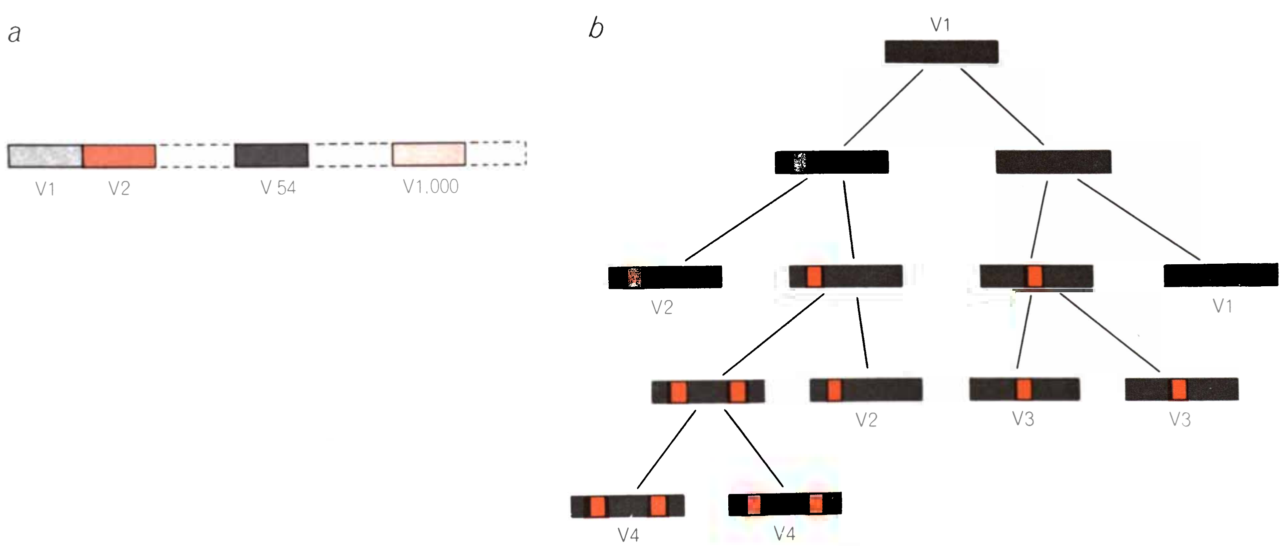
coloring or shading of identical residues in each position; dark and light shading indicates identities that occur in pairs at one position. Gaps have been introduced to maximize the homology. The numbering across the top is that of positions of residues in light chains.

						5					10					15					20			
I		ASP	ILE	GLN	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	CYS
		ASP	ILE	GLN	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	CYS
		ASP	ILE	GLX	MET	THR	GLX	SER	PRO	SER	THR	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	CYS
		ASP	ILE	GLX	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	ILE	THR	ILE	THR	CYS
		ASP	VAL	GLX	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	CYS
		ASP	ILE	GLN	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	ALA	SER	LEU	ARG	ASP	ARG	VAL	THR	ILE	THR	
		ASP	ILE	GLN	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	VAL	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	ALA	
		ASP	ILE	GLN	LEU	THR	GLN	SER	PRO	SER	PHE	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	
		ASP	ILE	GLN	MET	THR	GLN	SER	PRO	SER	THR	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	
		ASP	ILE	GLN	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	
		ASP	ILE	GLN	MET	THR	GLN	SER	PRO	SER	SER	LEU	SER	ALA	SER	VAL	GLY	ASP	ARG	VAL	THR	ILE	THR	
II		GLU	ILE	VAL	LEU	THR	GLN	SER	PRO	GLY	THR	LEU	SER	LEU	SER	PRO	GLY	ASP	ARG	ALA	THR	LEU	SER	CYS
		GLU	ILE	VAL	LEU	THR	GLN	SER	PRO	GLY	THR	LEU	SER	LEU	SER	PRO	GLY	GLU	ARG	ALA	THR	LEU	SER	CYS
		LYS	ILE	VAL	LEU	THR	GLN	SER	PRO	GLY	THR	LEU	SER	LEU	SER	PRO	GLY	GLU	ARG	ALA	THR	LEU	SER	
		ASP	ILE	VAL	LEU	THR	GLN	SER	PRO	ALA	THR	LEU	SER	LEU	SER	PRO	GLY	GLU	ARG	ALA	THR	LEU	SER	
		GLU	MET	VAL	MET	THR	GLN	SER	PRO	ALA	THR	LEU	SER	MET	SER	PRO	GLY	GLU	ARG	ALA	THR	LEU	SER	
		GLU	ILE	VAL	LEU	THR	GLN	SER	PRO	GLY	THR	LEU	SER	LEU	SER	PRO	GLY	ASP	ARG	ALA	THR	LEU	SER	
		GLU	ILE	VAL	LEU	THR	GLN	SER	PRO	ALA	THR	LEU	SER	LEU	SER	PRO	GLY	GLU	ARG	ALA	THR	LEU	SER	
III		ASP	ILE	VAL	LEU	THR	GLN	SER	PRO	LEU	SER	LEU	PRO	VAL	THR	PRO	GLY	GLU	PRO	ALA	SER	ILE	THR	CYS
	GLU	ASP	ILE	VAL	MET	THR	GLN	THR	PRO	LEU	SER	LEU	PRO	VAL	THR	PRO	GLY	GLU	PRO	ALA	SER	ILE	SER	CYS
		ASP									SER	LEU	PRO	VAL	THR	PRO	GLY	GLU	PRO	ALA	SER	THR	SER	CYS

PATTERN OF VARIATION of three different subgroups of one class of light-chain variable regions yields clues to their genetic origin. Each line represents a partial sequence (the first 23 residues) determined in the laboratories of H. D. Niall and P. Edman, C. Milstein, Norbert G. D. Hilschmann, Frank W. Putnam or Lee Hood. Each subgroup (*roman numerals*) has a characteristic sequence, indicated in each case by a dominant color or shade of gray. Within each subgroup there are variations (*black*) that arose from mutations. (*GLX* refers to positions where it was not yet definitely established whether the residue was glutamic acid or glutamine.)

tions of the constant region of the heavy chain turn out to have homologous amino acid sequences, that is, sequences more similar than could occur by chance. These portions are designated C_H1, C_H2 and C_H3, and each is homologous also to the constant region of the light chain, C_L. It is these constant regions that carry out functions of the molecule other than the binding of antigens. For example, C_H2 is believed to be bound by members of a complex family of serum proteins known as complement, thus beginning the series of reactions that is capable of killing cells, one of the aspects of the immune response.

The homology of the constant regions and the somewhat weaker homology of the variable regions to one another is demonstrated by directly comparing their amino acid sequences [*see bottom*



DIVERSITY of variable regions can be explained by three theories. A large number of genes, one for each variable region, could have arisen in the course of evolution (*a*). Alternatively, there could be one V gene, which mutates in an individual animal's body cells during development to produce the required variety (*b*). Finally, several V genes could evolve by mutation and be *illustration on pages 38 and 39*]. This is an unusual finding, and it means that the regions must be related in their evolutionary origins. It is likely that present-day antibodies have evolved by a process known as gene duplication. A primitive gene of a size sufficient to specify one homology region must have doubled and tripled, thereby forming a larger gene whose segments then became somewhat different from one another, as reflected in the sequences. By a similar process the genes for the two kinds of chain, heavy and light, appear to have had a common ancestor. This hypothesis, which was first suggested by Hill at Duke and S. Jonathan Singer of the University of California at San Diego, is strongly supported by the structure of the whole molecule.

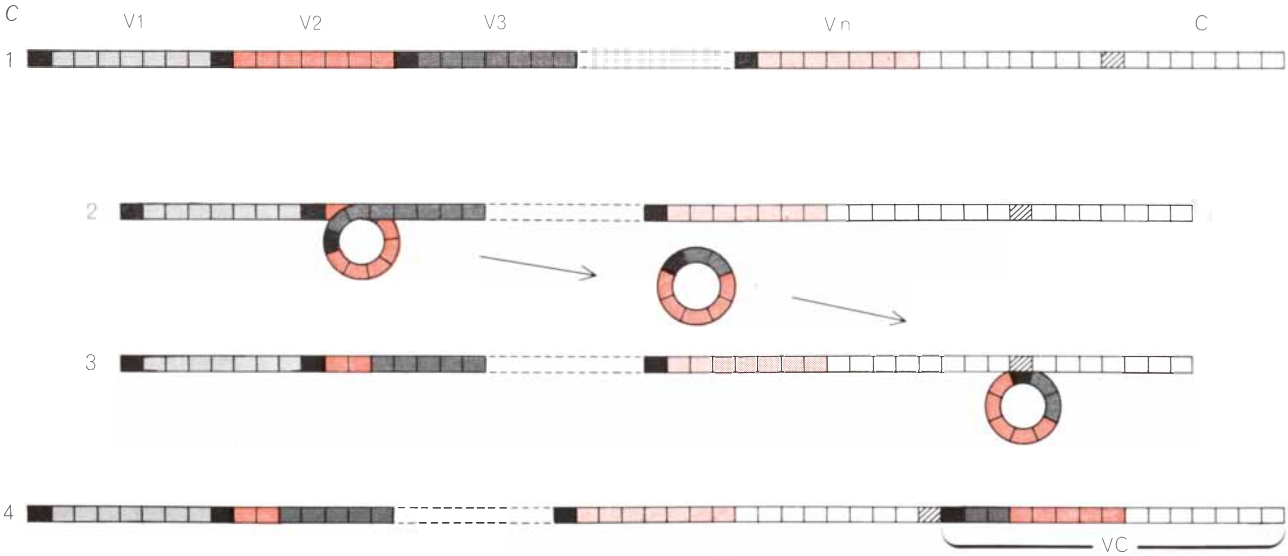
A comparison of the variable regions with the four constant homology regions shows that although they have roughly the same length, they have few sequences in common. Did they also arise from the same original gene? Probably, far back in evolution, but if so, they must have diverged rapidly as they carried out different functions of the antibody. Indeed, studies by C. Milstein of the Medical Research Council in England and by Lee Hood of the National Institutes of Health indicate that in each individual there must be more than one gene for each variable (V) region. Earlier, pioneering genetic investigations by Jacques Oudin of the Pasteur Institute and by Rune Grubb of the University of Lund had laid the groundwork for the conclusion that there is only one gene for each constant (C) region. Since the polypeptide chains of antibodies appear to be made in one piece, as are other proteins, it seems that information from two genes is required to specify a single polypeptide chain. This is a unique situation, because in all proteins that have so far been investigated a single gene is enough to specify a single polypeptide chain.

The analysis of antibodies, then, poses two special problems: How can the V genes vary so that many different V regions are made in each individual? And how can such a V gene, which evolved to give the antibody system a range of different combining sites, be joined with a C gene that evolved to specify the constant portions of the chains and thus carry out effector functions?

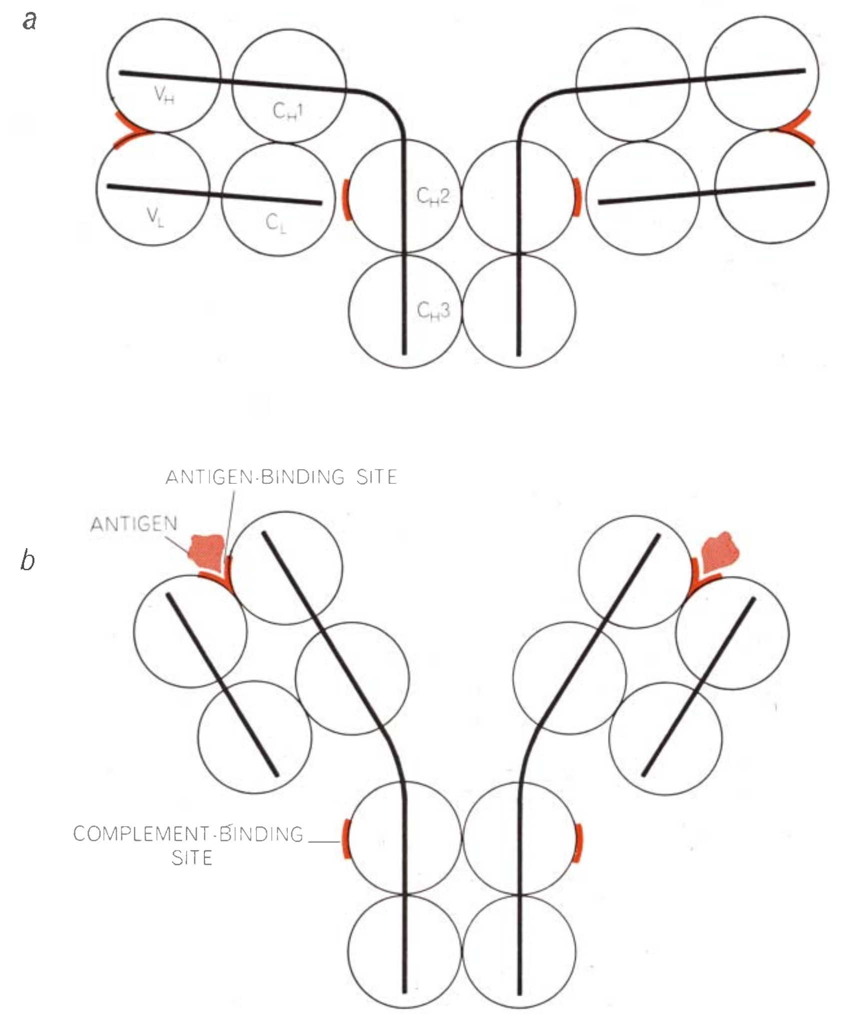
Before attempting to suggest answers to these questions, let us look at the actual variation seen in V regions [*see top illustration on opposite page*]. The variation has several important characteristics. First, the genetic-code dictionary (in which each amino acid is coded for by a triplet of three DNA nucleotides) reveals that the variation arises from one-base changes in the code words for the amino acids in each variable position. This means that the variations were caused by mutations, just as in the case of other proteins. Second, not every position in the V region varies. For example, no one has ever observed that any of the cysteines that contribute to the sulfur bonds are missing or replaced by another amino acid. Third, certain positions seem to have more variations than others, although the number of examples is still too small for one to be completely sure of this. These last two observations mean that the variation is not random but is the result of some kind of selection. We can conclude that, as in other proteins, both mutation and selection are responsible for antibody variation.

The question about the origin of variability can be resolved into two more pointed questions. They are: Where and when do these processes occur? How many V genes are required? One theory suggests that the variation and selection occur during evolution, so that in an animal each different V region has a corresponding V gene. This would require a very large number of V genes in the germ cells. Another theory states that there is one V gene, which mutates not during evolution but somatically—in the body cells of the individual animal—and that the mutant cells are somehow selected. A third theory, which I favor, is that there are a few V genes, which have mutated and have been selected in evolution but which then recombine somatically in the cells of the animal to provide the broad variational pattern. This last theory has the advantage that the same processes that recombine the V genes could also accomplish the fusion of V and C genes that is required to make a single antibody chain; one can thus account with one mechanism for the two questions: How is antibody diversity created? How are V and C genes joined?

The mechanism may be one that is somewhat similar to mechanisms that have already been described for infection of the bacterium *Escherichia coli* by



selected during evolution, and then be recombined in many different ways in the animal (*c*). In this process the evolved genes (*1*) might recombine to form a ring-shaped V-gene episome (*2*), a variant gene composed of sequences from adjacent V genes. The episome might be translocated and become integrated with the C gene (*3*) to form the complete VC gene that is expressed (*4*).



BINDING OF ANTIGEN may stabilize a change in the shape of the antibody that triggers a series of immune reactions. Here the antibody is drawn as a flexible grouping of compact domains, with the chain structure suggested by the heavy black lines (*a*). The antigen is bound by the variable regions, perhaps facilitating a pivoting movement of the molecule that exposes effector sites, such as the complement-binding site, in the C regions (*b*).

the bacterial virus lambda. A piece of DNA (a V gene) could be removed from a row of V genes (each having evolved to be slightly different) and could then be inserted and fused with a C gene. If the DNA is removed as a ring, the process would effectively permute the sequence, leading to variation [*see bottom illustration on preceding two pages*]. As mentioned above, the alternative somatic theory is that a single V gene is mutated and then translocated, following which the cell making the VC product is selected for or against within the body. Which of these theories is correct remains to be defined, but both theories require a process of assembly of a VC gene from separate V and C genes. This requirement suggests that it may be by the translocation of genes that the cell achieves its goal of making just one kind of immunoglobulin. Molecular differentiation of this type is so far unique to the immune system, but it may in fact turn out to be important in other systems of differentiation among higher organisms.

Although the molecular details of the mechanism of translocation and recombination remain hypothetical, there is some recent evidence that we are on the right track in concluding that antibody variation is somatic in origin. The evidence comes from studies of the genetics of mouse immunoglobulins done with my student Paul D. Gottlieb. These experiments are still in their early stages, however, and the actual mechanism of variation has so far not been demonstrated.

The origin of the required diversity and the restriction of that diversity to one kind of antibody for each cell seem to be mirrored in the structure of the antibody molecule. What does antibody structure tell us about how these molecules actually carry out their functions? It is clear that antibodies have two kinds of task: first, recognizing the antigen, and second, doing something to the antigen or initiating a chain of cellular responses. The task of antigen-binding is delegated to the V regions. The more dynamic role of influencing cellular responses, the binding of complement and the initiation of processes that alter the antigen appears to be the function of the C regions. In some sense the antibody molecule must behave as a switch: binding the antigen must change the antibody's state in such a way as to "turn on" its effector functions. It is known that protein molecules can act as switches by changing their shape. There is now a hint that this may be the case for antibodies. When antibodies are viewed in the electron microscope after combination with antigens, their dimensions appear to be smaller than those of unbound immunoglobulins measured by X-ray scattering in solution. This raises the possibility that the binding of the antigen causes a rearrangement of the structure of the antibody molecule, which is known to be somewhat flexible. The rearrangement might consist, for example, of a pivoting movement involving part of the constant region of the heavy chains [*see illustration at left*]. Binding sites for complement might be exposed by this pivoting, as well as other sites for different effector functions. Similar mechanisms may be involved in triggering the antibody-producing cell to divide and mature.

As these hypotheses indicate, much remains to be done in the field of antibody structure. What has been learned indicates that the antibody system is special and that it may have evolved to solve its problem of molecular recognition in a unique way. There remains the intriguing possibility, however, that the special genetic mechanisms hinted at by the differentiation of antibody-producing cells will be found in other systems of cellular differentiation; certainly there are at least conceptual similarities to some other systems of pattern recognition, such as those of the central nervous system. In any event, whether the immune system turns out to be unique or representative of a more general type of evolutionary development, we can expect practical consequences of great significance for fields of study such as immune tolerance, organ transplantation and autoimmune disease to flow from a continuing analysis of the structure of antibodies.

We want to be useful ...and even interesting

Kodak

Polar ladder

"Solid state" has graduated from a branch of physics to a point made in equipment salesmanship. Though students of the liquid state have achieved less influence, it is widely understood that some liquids are more polar than other liquids and that this determines what dissolves what how fast. Furthermore it makes chromatography work. For a ranking by ascending polarity of 87 very readily available solvents write Eastman Organic Chemicals, Eastman Kodak Company, Rochester, N.Y. 14650.

Photography and coherence

Howard M. Smith's book "Principles of Holography" has to be ordered from a bookseller, not from us. Honor done to Dr. Smith for the usefulness of his exposition does us honor also, since he is one of us. An author setting out to do a good job under that title gets beyond the scope of our own literature on how to derive fun or profit from Kodak products. Principles and practice must not be kept apart for too long, however. Products useful in the practice of holography are subject to high-speed evolution. Bruce Burdick, Eastman Kodak Company, Rochester, N.Y. 14650 is the man whose job it is to keep in touch with those concerned. **Burdick's number is 716-325-2000, ext. 3440.**

One is taught to look onward and upward. The possibility must be discounted that in the year 2020 nobody will want to make a hologram or remember how it was done. On the contrary, one must assume that by then the capture and storage of imagery by causing photochemically the deposit of substances in geometrical analogy to an original subject will seem closely akin to the paleolithic hunter's beautiful representations of the lccal fauna on the cave wall. That kind of photography may by then have resumed its close relationship with the art of painting from which it had diverged (and which has been severely shaken by the schism). For everyday utility in 2020, images would be handled by recording, modifying, and regenerating actual wave fronts (rather than only radiance patterns), just as an acoustic diaphragm re-creates what was in Bach's head. In our line of work it would be folly to place no bets on this.

Not being alone in this optimism, we must separate our work on the applications of coherent optics from our efforts to serve others who have ideas of their own. To the Optical Society of America earlier this year, R. L. Lamberts and C. N. Kurtz—fellow laborers of Howard Smith's in the Kodak Research Laboratories—presented a new recipe for a hologram-developing solution that is followed, not by fixing, but by a bleach. Desilvered phase holograms are known to diffract light much more efficiently than amplitude holograms, but with the brighter image degraded by a veiling flare. Lamberts and Kurtz attribute the flare to accentuation of the lower frequencies by microcorrugations forming on the gelatin surface during drying. At the higher frequencies, displacements are too small to create a relief pattern, but the refractive index periodicity left from development action remains for all frequencies. The new recipe pits the relief effect *against* the index effect, instead of with it.

If interested in the latest version of the recipe, ask Mr. Burdick.

We may also be of assistance to the school of holography that places faith in amplitude and wants more silver left. If Burdick answers some of them with a suggestion about adding a little sugar to their developer, he is not being funny.

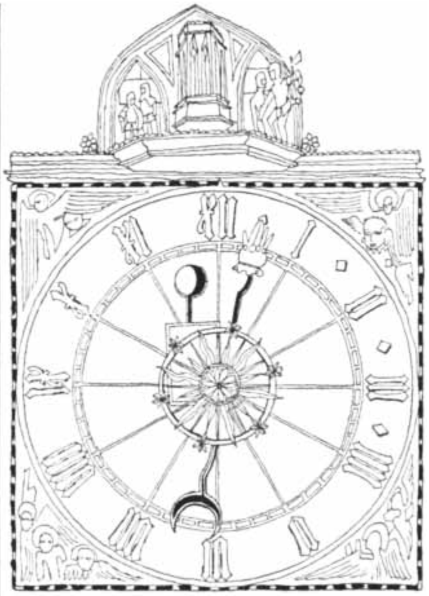
When he checks into town, the color on your tube improves

Ward Vuillemot is one of seven Kodak engineers who spend all their time visiting the TV stations of the U.S.A., a nation whose strong dedication to private enterprise brings on television engineering problems different from the ones we work on in England for the BBC.

It's a matter of the incentives that power U.S. television and the play of competition among manufacturers of complex broadcasting components that must all work together. Each manufacturer of these components services its own product but also welcomes counsel to its customer stations from an optically and electronically capable source that is not competing in the league but wants to see the best possible color rendition on the air.

That means us. We make color film for the TV industry. So do others. Furthermore, color film is not the only way of capturing color images. Thus we, too, enjoy competition. Therefore we arranged for Ward Vuillemot and his colleagues to prepare for their mission at two truly non-commercial nearby fountainheads of TV technology, the Ryerson Institute of Toronto and the Canadian Broadcasting Corporation.

We figure the best way to keep a station from ever blaming Eastman film for off-color is to make the station's output signal look good all the time.



SCIENCE AND

Relativity Revisited

Two independent tests of the bending of electromagnetic radiation by the sun's gravitational field have provided the strongest support yet for the value predicted by Albert Einstein's general theory of relativity. Whereas the standard test has been to measure the apparent displacement of stars near the sun at the time of total eclipse, the new tests depend on the apparent displacement of a strong radio source, the quasi-stellar object 3C 279, when it passes behind the sun. The deflection of light predicted by Einstein's theory is 1.75 seconds of arc. The measured deflection is 1.77 plus or minus .20 seconds according to one of the new tests and 1.82 plus .24 or minus .17 seconds according to the other.

In both experiments the position of 3C 279 was compared with that of a nearby quasar, 3C 273, using two radio telescopes coupled to act as an interferometer. Only 3C 279 passes close enough to the sun for its radio waves to be deflected. One interferometer consisted of a 130-foot dish antenna linked to a 90-foot dish 3,500 feet away at the Owens Valley Radio Observatory of the California Institute of Technology. The observers were G. A. Seielstad, R. A. Sramek and K. W. Weiler. The second interferometer consisted of a 210-foot dish and an 85-foot dish 13.4 miles apart at the Goldstone Space Tracking Station operated by the Jet Propulsion Laboratory. The observers were Duane O. Muhleman, Ronald D. Ekers and Edward B. Fomalont of Cal Tech.

Although probably more accurate than any previous observations of the gravitational deflection of radiation, the new results do not rule out an alternative to Einstein's theory, the scalar-tensor theory of gravitation, that predicts a deflection of about 1.65 seconds of arc. This value falls within the lower limit of the radio results. The team that conducted the experiment with the larger dishes and the longer base line believes future observations will improve the accuracy by a factor of three and thus make possible a decisive test between the two theories.

Accelerator Accelerated

The next plateau in the construction of super-high-energy particle accelerators may be reached sooner than expected. The latest word from the National Accelerator Laboratory in Batavia, Ill., where the new U.S. high-energy proton synchrotron is under construction, is that a proton beam may be achieved by mid-1971, a year earlier than the originally scheduled date and considerably before the experimental areas and the rest of the laboratory will be completed. Moreover, it now appears possible that the protons can be accelerated to an energy close to 500 billion electron volts (GeV) at reduced intensity not long after the synchrotron is brought into operation; this would be well above the 200 GeV originally planned as the start-up energy. These upward revisions in the expectations of the accelerator project are contained in the annual report to the National Accelerator Laboratory Users Organization by the laboratory's director, Robert R. Wilson.

The advanced schedule of the National Accelerator Laboratory machine, announced at a time when construction money from the Atomic Energy Commission has become available at a substantially lower rate than originally scheduled, is attributable to a number of factors. Central among these is the decision to concentrate on the construction of the accelerator itself, postponing work on some other parts of the laboratory. In addition, actual bids on many components turned out to be lower than expected, owing to simplifications in design. Recent technical developments have also made it possible to install a power supply adequate for an energy of 500 GeV at a smaller cost than was originally estimated for 200 GeV.

Meanwhile the European Organization for Nuclear Research (CERN) has not yet reached agreement on a site for its projected 300-GeV machine, which might ultimately be boosted to 800 or 1,000 GeV. Also said to be in the planning stage is a Russian accelerator capable of reaching 1,000 GeV. The Russian 76-GeV machine at Serpukhov is currently the most powerful accelerator in operation.

Two Years behind the Drill

Completion early this month of the *Glomar Challenger's* 12th voyage of exploration will mark the halfway point in a four-year program under Federal auspices that with unique success has wedded the drilling technology of the petroleum industry to the ability to analyze ocean-botton sediments that has developed among oceanographers in recent years. The ship, operated by a petroleum exploration group, Global Marine, Inc., has been under contract since 1968 to the Scripps Institution of Oceanography, manager of the Deep Sea Drilling Project. The program is being conducted under a $35 million contract with the National Science Foundation.

In the interval between "Leg One," the initial voyage from Texas to the Atlantic in the summer of 1968, and "Leg 12," a voyage out of Boston that will end in Lisbon soon, drillers and observers aboard the *Glomar Challenger* have traveled Atlantic, Pacific and Gulf of Mexico waters for the equivalent of more than two trips around the world at the Equator. Drilling a total of 6,500 hours, they have brought to the surface from holes that have sometimes extended well over half a mile below the ocean floor more than 1,500 core samples with a cumulative length in excess of five miles. The maximum depth of water plumbed (20,146 feet) was encountered off Guam in 1969. The deepest penetration below the ocean floor (3,334 feet) was made off Miami in 1970.

Besides breaking all records for marine drilling the *Glomar Challenger's* crew has now demonstrated a totally new skill: the ability to pull up the drill string in mid-job, replace a worn cutting head and then resume drilling in the same hole miles below the keel. The two years' work has seen a number of significant contributions to the understanding of the history of the earth. For example, core analysis has now conclusively demonstrated that the suboceanic crust is young compared with much of the continental crust. The oldest underwater material known is a specimen of sediment near the Bahamas that was deposited in Middle Jurassic times, some 160 million years ago. Core analysis has also confirmed earlier evidence that the sea floor is continually spreading as magmas well up along the mid-ocean ridges. Proof of sea-floor spreading has in turn helped to convert the hypothesis of continental drift, once considered radical, into respectable doctrine.

Suspension

The defoliation of South Vietnam has been suspended and may not be resumed on a large scale. More than 4.5 million acres have been sprayed with chemicals since 1961 in an effort to deny cover to enemy troops and destroy their sources of food. The suspension was based on a combination of factors, according to *The New York Times.* Because the most extensively applied defoliant chemical, 2,4,5-T, had been implicated in genetic damage, the Department of Defense ordered its use stopped in April. Then, at the end of that month, the Cambodian invasion provided an alternative mission for the transport planes that had been employed in defoliation: they were diverted to fly out captured material.

It was expected that spraying would be resumed with the end of U.S. ground operations in Cambodia, but on a smaller scale, with the emphasis on crop destruction and the clearing of limited areas near U.S. and South Vietnamese bases. The U.S. has taken no steps to renounce defoliation. It has been officially maintained that herbicides, like tear gas, cannot be classified as genuine chemical weapons.

Death by Glacier

The Peruvian earthquake of May 31, which took some 50,000 lives, reminds men once again that their perch on the crust of the earth is precarious; Nature disposes of vaster forces than human technology can cope with. The truism was dramatized by a preliminary report on the destruction of the town of Yungay by Louis Lliboutry of the French National Council for Scientific Research, a member of a team of seismologists, geologists and civil engineers dispatched to the stricken area by UNESCO. According to Lliboutry, it was a glacier gone wild—not a bursting lake, as had first been reported—that wiped out Yungay and its 15,000 residents.

Yungay lay in the Huaylas Valley of the Andes Mountains, 10,000 feet below Mount Huascaran, nine miles away. The earthquake dislodged about a million cubic yards of ice from a 2,600-foot cliff on the mountain. The ice crashed onto a glacier below the cliff and sent a wall of mud—30 million cubic yards of ice and water and 65 million cubic yards of earth—racing down the valley of the Rio Santa. The mudflow covered the nine miles in less than two and a half minutes, reaching the unglacial speed of more than 250 miles per hour. It surged over a ridge and overwhelmed the city, covering it to an average depth of 10 feet. Only a few dozen inhabitants survived. Of all the works of man, only the branches of four palm trees planted in the Plaza de Armas remain visible. Lliboutry reported that aerial photographs show that a similar mudflow swept down the valley once before. That was between 1,000 and 10,000 years ago.

Orbital Rendezvous

A new concept that enzymes facilitate chemical reactions by precisely guiding the angles of approach of atoms in the reacting compounds has been proposed by Daniel E. Koshland, Jr., of the University of California at Berkeley. Koshland presented evidence for this concept, which he calls orbital steering, at the Seventh International Symposium on the Chemistry of Natural Products, held in Riga in June.

Koshland and his co-workers, Dan R. Storm and Kenneth Neet, studied the simple reaction in which ethyl alcohol and acetic acid combine to form ethyl acetate, with the release of one molecule of water for each molecule of product. In an effort to catalyze the reaction, the Berkeley workers attached the reactant molecules to specially selected "holder" molecules in the form of organic ring compounds. Some of the holder molecules enabled the alcohol and acetic acid to react a million times faster than they do in the absence of a catalyst. Koshland and his colleagues observed that the acceleration was critically related to the angles at which the reactants were gripped by the holder molecules. Evidently the carbon atom in the COOH group of the acid molecule has to be presented to the oxygen in the alcohol molecule at exactly the right angle. When sulfur was substituted for oxygen in the alcohol, forming ethyl mercaptan (C_2H_5SH), there was a sharp drop in the reaction rate even though the sulfur-substituted alcohol normally reacts with acetic acid about as readily as ordinary alcohol does. This suggests that the most favorable angle of approach for sulfur and carbon in this reaction is different from the preferred angle for oxygen and carbon. Koshland and his co-workers conclude that the reaction is facilitated when the orbital paths of the electrons that surround the reacting atoms are in correct alignment; hence the term orbital steering.

The Diversity of Asteroids

The thousands of asteroids that travel around the sun in the orbital space between Mars and Jupiter, whether they are the remains of a shattered planet or the building blocks of an uncompleted one, are in any case not all alike. This is the conclusion reached by Thomas B. McCord and Torrence V. Johnson of the Massachusetts Institute of Technology and John B. Adams of the College of the Virgin Islands after several years of measuring the sunlight reflected by some of the largest asteroids. Ceres and Pallas, each more than 400 miles in diameter, and Vesta, with a diameter of about 250 miles, were examined at a series of narrow-wavelength bands that ranged from the near infrared to the ultraviolet. Although Vesta is smaller than the other two bodies, it is the brightest of all the asteroids and is the only one so far to yield unequivocal evidence of its composition.

Working with the 100-inch and 60-inch telescopes on Mount Wilson and with the 60-inch instrument at the Cerro Tololo Inter-American Observatory in Chile at various times since 1967, the three investigators scanned the light reflected from the surface of the asteroids over a range of wavelengths from 1.1 microns to .3 micron. The reflection from Vesta showed a strong absorption band near .9 micron and weaker absorption features between .7 and .4 micron. The .9-micron band is not present in the reflection from Pallas and is apparently missing in the reflection from Ceres.

Seeking to determine the composition of Vesta's surface, the investigators measured the spectral reflectivity of a number of complex minerals, including samples from meteorites. Among these was a stony meteorite, found in Mexico in 1950, that was being examined at the

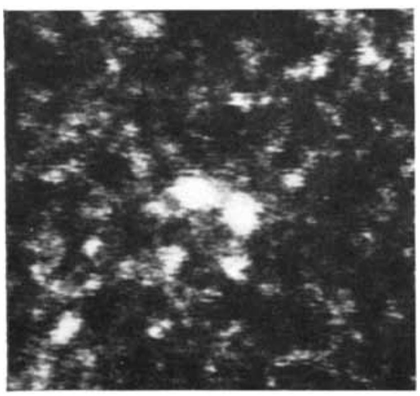
California Institute of Technology. Known as the Nuevo Laredo meteorite, it belongs to the class of stones known for their lack of the spindle-like structures called chondrules. The curve of the Nuevo Laredo meteorite's spectral reflectivity proved to be a nearly perfect match with the curve yielded by Vesta. Reporting in *Science,* McCord, Johnson and Adams conclude that the mineral composition of Vesta's surface is similar to the composition of basaltic achondrites, whereas the surface of Pallas (and possibly the surface of Ceres) is not.

Visible Atoms

The pair of bright spots in the photograph below are two individual uranium atoms, located on each side of a long-chain organic molecule and seen against a dark background consisting of a thin film of carbon atoms. The images of the atoms were enlarged more than a million times and made to appear on an oscilloscope screen by means of a new technique that involves an improved high-resolution scanning electron microscope designed and built by Albert V. Crewe of the University of Chicago.

Crewe's microscope, developed with the support of the Atomic Energy Commission, consists of an electron-optical system that produces a focused spot of electrons about five angstroms in diameter. The specimen is placed at the focus, and the electron beam is scanned across it in a square raster 600 lines wide. The electrons scattered from structures in the specimen are used to generate the image on the oscilloscope. Although the resolving power of Crewe's device (five angstroms) is not as great as that of some conventional electron microscopes, the contrast is better.

The experimental procedure, which involves constructing various molecules containing heavy atoms whose spacing is greater than five angstroms, was worked out by Crewe in collaboration with two graduate students in biophysics at Chicago, Joseph Wall and John Langmore. An article describing their work appears in a recent issue of *Science.* In addition to photographing pairs of uranium atoms in molecules produced by reacting uranyl acetate with benzene-tetracarboxylic acid, the group has also succeeded in imaging single uranium atoms in molecules of uranyl acetate and strings of thorium atoms set at regular intervals along molecules produced by reacting thorium nitrate with benzene-tetracarboxylic acid. In every case the bright spots on the oscilloscope screen were close to the calculated visibility factor, and their geometric arrangement corresponded to the expected one.



Pair of uranium atoms under the microscope

According to Crewe, the new technique should be particularly valuable in analyzing chromosomes and cancer cells. In addition, he notes, "the ability to see the atom, even of high atomic numbers, will certainly enlarge the scope of biochemistry and molecular biology because many chemical techniques have been established whereby foreign atoms can be introduced at known sites in complex molecules. The ability to see such atoms may make it possible to determine shapes of molecules and their relationships." Crewe foresees that within two years atoms as small as iron and copper should be made visible. Eventually, he adds, "we will be able to show different atoms in different colors on the same microgram."

Mysterious Hepatitis

The incidence of viral hepatitis in the U.S. has been increasing in recent years. What causes this disease, the symptoms of which include a general feeling of malaise, vomiting, black urine and a yellowish skin color? It has been assumed that the cause is a single virus, but at the same time physicians generally distinguish between two forms of the disease. One form is infectious hepatitis, which is thought to have an incubation period of between 15 and 40 days and is believed to be contracted through close contact between individuals. The other is serum hepatitis, an infection with an incubation period estimated at between 60 and 160 days that is contracted through the administration of plasma or other blood products contaminated with the hepatitis agent. The results of recent investigations, however, may make it necessary to revise commonly held ideas about the nature of the hepatitis virus and how it is transmitted.

In 1964 Baruch S. Blumberg, a geneticist on the staff of the Institute for Cancer Research in Philadelphia, accidentally discovered an unusual antigen in a blood sample taken from an Australian aborigine. In the next few years Blumberg and other workers clearly established that the antigen, now called the Australia antigen, is associated with viral hepatitis in man. Some investigators contend, however, that the Australia antigen is associated only with serum hepatitis, whereas others believe it is involved in both forms of the disease.

Fresh support for those who say that the Australia antigen is associated only with serum hepatitis is provided in *The Journal of the American Medical Association* by Saul Krugman and Joan P. Giles of the New York University School of Medicine. Since 1956 Krugman and Mrs. Giles have been investigating the disease at the Willowbrook State School, a Staten Island institution for retarded children where the disease is endemic. They have found two distinct strains of hepatitis agent. One strain resembles the agent of serum hepatitis in that it is immunologically related to it and has an incubation period of between 65 and 96 days. The other strain resembles the infectious hepatitis agent and has an incubation period of 32 days. Both strains cause hepatitis when they enter the body through the digestive tract or the bloodstream. When the physicians tested serum from the blood of patients carrying the strain resembling the infectious hepatitis agent, they found no evidence of the presence of the Australia antigen. The antigen was present only in serum taken from patients carrying the strain resembling the agent of serum hepatitis.

Krugman and Mrs. Giles conclude that if serum hepatitis can be contracted from ingested material, then it too is infectious. Therefore, they argue, the two forms of hepatitis differ not in the way they are transmitted but in that each is caused by a different agent.

The agents themselves still constitute a puzzle for virologists. According to Lewellys F. Barker of the National Institutes of Health, the Australia antigen is a tubular or spherical particle (or perhaps a region on such a particle). These particles almost certainly lack any nucleic acid. Barker therefore concludes that either the Australia antigen is a "unique type of infectious agent"—one whose activities and reproduction are not guided by nucleic acid—or the tiny rods and spheres Barker has observed with the electron microscope are incomplete, noninfectious viral components. No agent has yet proved to be associated with infectious hepatitis.

She'd hug us if she could.

More precisely, she'd hug our John Welsh.

One of John's customers manufactures concrete statues. He casts them in 900 pound steel molds which must be cleaned of residual concrete with a hot mineral acid after each casting.

Hot acid cleans away concrete easily. So easily, that if left unchecked, it can also attack and pit the steel molds. That's why John's customer was testing MAIN™ 33S acid inhibitor—for the safety, economy and prolonged bath life it promised. But he didn't expect to test it under such severe conditions.

Using his electrically powered crane, he lowered one of his molds into the hot mineral acid. And then it happened. The power failed.

With no power to lift the mold out of the acid, John's customer was sure it would be corroded beyond use by the time power was restored.

And it would have been too if it weren't for MAIN 33S. This unscheduled acid exposure test proved that MAIN 33S establishes a barrier between the steel mold and the acid, preventing corrosion.

John knew MAIN 33S could effectively inhibit acid corrosion under normal acid cleaning conditions. But it took his customer's particular acid cleaning operation and a power failure to substantiate our claims that MAIN 33S is effective even under severe acid exposure conditions.

This MAIN 33S success is only one example of the way Abbott Chemicals works to help you find solutions to your chemical problems.

One of our jobs as the chemical marketing arm of Abbott Laboratories is to find industrial applications for many of the 1000 chemicals Abbott synthesizes each year.

To do this, we rely heavily on our people. The John Welshes who help their customers find solutions to their chemical problems. Who find new uses for our existing chemicals. Who uncover new applications for never-before-used chemicals.

In the process, we've developed a series of economical polymer catalysts used in manufacturing urethane foams.

A better antioxidant/stabilizer for middle distillate fuels.

And a special polymer catalyst for overprint varnishes and other specialty coatings.

Helping solve your problems is what our product development is all about.

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Abbott Chemical Products Division

What is U.S. Steel doing

to help grow more food?

In ten years there will be 25 million more Americans to feed. We'll either have to spread our food thinner and thinner, or produce much more.

U.S. Steel is helping to grow more food, through our Agri-Chemicals Division.

At the Atlanta research center, we do basic research using soil samples from across the country.

The samples are carefully analyzed to help tell us how to improve soil in different areas.

What we learn in the laboratory we put to work on farms coast to coast.

We'll take soil samples.

Analyze them.

Mix the specific nutrients the farmer needs.

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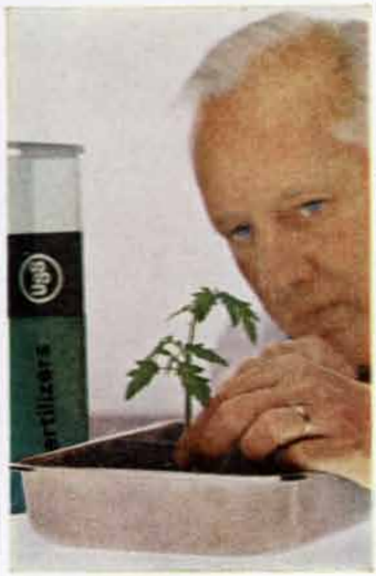
In many cases, the output of farm land can be easily doubled compared with untreated land. And our research continues. We're finding ways to help grow more food.

Which means that in the years to come you can still worry about *what* your next meal will be, instead of *when*.



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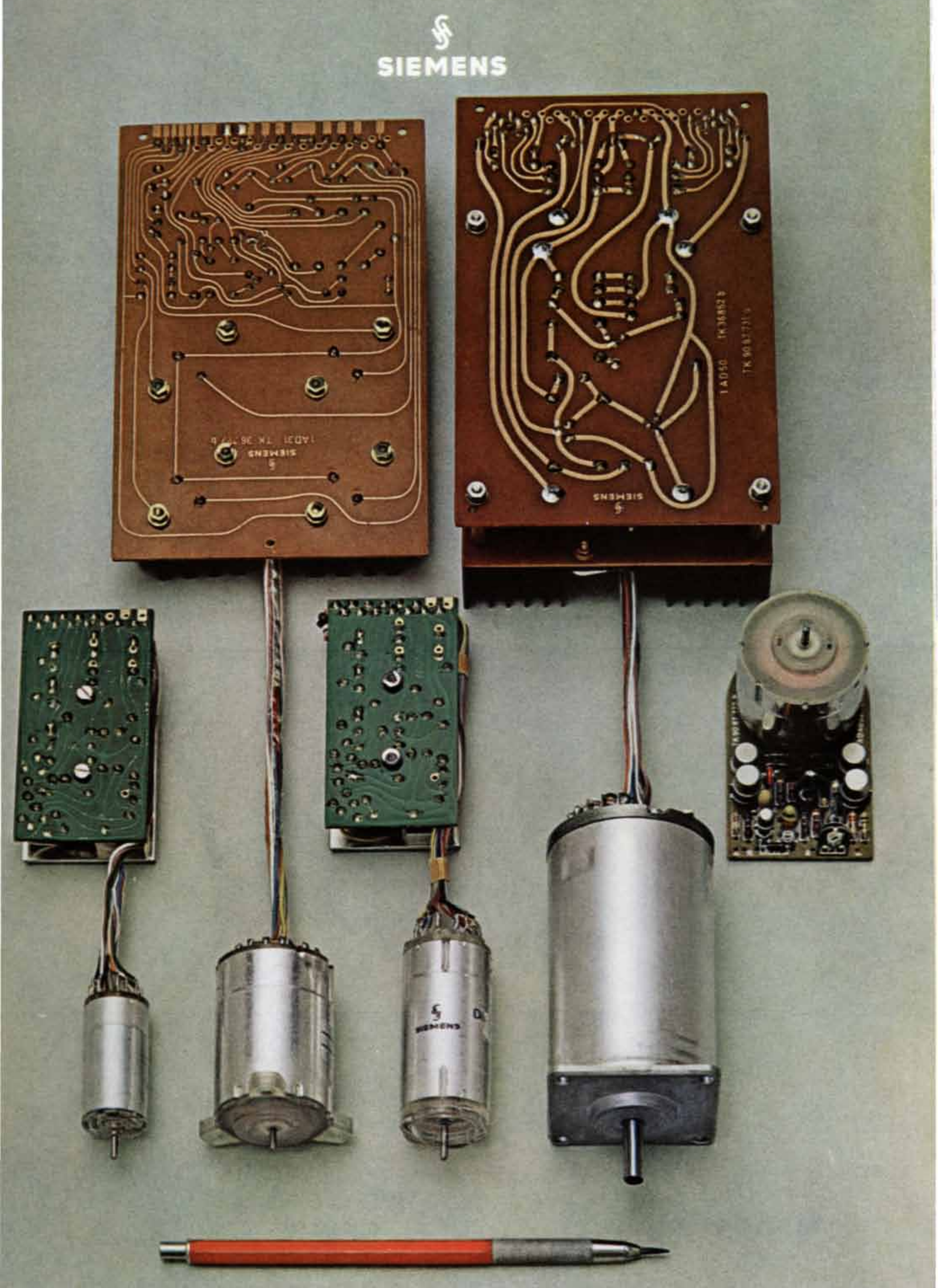
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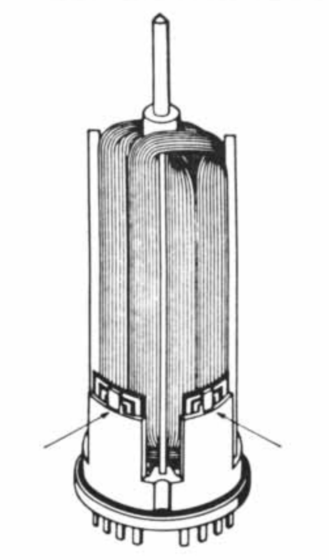

Arrows indicate Hall generators.

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Siemens solid-state dc motors make dc motors practical for some previously impractical applications. For example, leased equipment, such as in devices for data processing systems, are ideal applications for this versatile motor. Such equipment can now benefit from accuracy of dc motors without the need for frequent costly brush replacement. Available in a range of sizes up to 7 oz./in, Siemens solid-state dc motors and gear motors are being widely used in tape recorders, medical instruments, missile guidance systems and other precision applications.

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A World Agricultural Plan

The Food and Agriculture Organization of the United Nations has developed an integrated program to close the gap between the curves for food production and population growth by 1985

by Addeke H. Boerma

There have been frequent prophecies of famine on a global scale since Thomas Malthus published his essay on population in 1798. So far demographers and scientists echoing Malthus' forebodings have always been proved wrong, but by the beginning of the second half of this century there were ominous signs of a steadily widening gap between supply and demand for food in the developing countries. At that time many of these countries had only recently been freed from colonial rule, and some of them lacked adequate financial and technical resources to immediately become self-supporting. The gap was reflected in rapidly rising imports of staple cereals, particularly in the Near East and Asia, and by mounting requests for food aid through such channels as the program of U.S. Public Law 480, the World Food Program and charitable foundations.

History of the Plan

It was against this background that the first World Food Congress was convened in Washington in 1963 under the Freedom from Hunger Campaign, a private group that raises funds and provides other support for the Food and Agriculture Organization of the United Nations (FAO). It was decided that the FAO should be asked to prepare a survey of the world food situation in relation to population and overall economic development, together with a plan for action that would indicate the long-term prospects for closing the food gap. It soon became apparent that even a study undertaken within such broad terms of reference would be inadequate. The scope of the proposed survey was therefore widened and deepened still further by the FAO's governing conference of member states. The conference decided that the study should become a "world plan for agricultural production, trade and development," highlighting the national and international actions needed to redress the alarming imbalance between food and population currently afflicting the world.

The mandate was fulfilled through four years of interdisciplinary work. Regional studies were conducted in Africa south of the Sahara, in Asia, in Latin America and in the Near East. An overall world study summed up the regional work and highlighted its conclusions. These findings, projections and policy recommendations, which became known as the Indicative World Plan for Agricultural Development, were submitted in provisional form to the FAO's Fifteenth Conference in November, 1969.

The plan, encompassing 23 years from a base year of 1962 to horizons of 1975 and 1985, is intended to provide a framework within which national and regional programs can be developed. It is hoped that governments will be able to use the plan to create and implement agricultural policies, and that it may also form a useful standard of reference for the resolution of conflicts of production and trade policies between nations. Moreover, it should serve as a guide to both donors and recipients of international aid. In this respect the plan is also intended to focus the activities of the FAO itself on the major operational priorities of world agriculture.

The plan aroused enormous interest among member nations participating in the FAO's Fifteenth Conference. Although it became apparent from the discussions that some countries hoped for a more complete blueprint for development from the plan, which had perhaps been oversold when it was first conceived, reaction was largely favorable. Few speakers disagreed with its main goals and recommendations, the chief critics being the South American countries, which objected not to the overall concepts of the world study but to the growth rates considered feasible in the provisional study for their region. These rates the South Americans believed to be too low to meet national aspirations. Nevertheless, the South Americans made plain their interest in maintaining global planning by proposing a resolution, approved by the conference, that called for the continuation and strengthening of such work in close collaboration with regional and national planners. The representatives hoped that this intensified effort would fill any gaps in the plan, and that it would provide a more balanced long-term view of the problems facing agriculture in both developing and developed countries.

It can be fairly concluded that the Indicative World Plan has succeeded in achieving its main objective: to provide a broad framework of guidelines for the planning of future world agricultural development, based on a reasoned analysis of the main issues likely to arise in the 1970's and the early 1980's. Since the plan was the focal point for the Second World Food Congress held at The Hague in June, and is also the main source of agricultural policy for UN strategy for the Second Development Decade (1970–1980), this seems a particularly good time to examine its main conclusions and recommendations.

The World Food Problem

The Indicative World Plan is both an attempt to look into the future and an effort to influence the future by proposing specific objectives for the agricultural sector together with recommendations for their attainment. Achieving these goals will clearly be difficult and challenging. First and foremost is of course the problem represented by the race between food and population. In 1965 there were 1.5 billion people living in the developing or less developed countries, which the UN classifies as Zone C countries. This excludes mainland China, whose population was then estimated at between 700 and 800 million. By 1985, assuming that the "medium" UN population-growth projection of 2.6 percent is accurate and that there is no world cataclysm, the population of Zone C will have risen by a billion to 2.5 billion. Neither present efforts in family planning nor rising income in developing countries is likely to affect this rate of growth significantly. Since population in the economically advanced countries increases much more slowly, 85 out of every 100 additional persons between 1965 and 1985 will be in the poor countries, including China, many of which are already overburdened by the size of their population.

This growth of population alone would require an 80 percent increase in food supplies by 1985 compared with 1962, without any improvement in quantity or quality of individual diets. Success in raising income levels along the lines of the most optimistic projections of the plan's economic model, and consequent improvements in purchasing power, would increase the demand for food by 142 percent above the 1962 level, an average geometric rate of increase of 3.9 percent per year. The trend in food production over the decade 1956–1966 for the developing countries as a whole was only 2.7 percent per year.

An unchecked continuation of this trend would result in a gap between demand and supply that, if it had to be filled by imports from other parts of the world, would by 1985 cost the developing countries $43 billion per year (assuming constant 1962 prices). Shortages of staple cereals and animal protein would be particularly acute. For Asia, the Near East and northwestern Africa cereal imports would theoretically be required exceeding 90 million metric tons (nine times those in 1962); otherwise 100 million hectares would have to be diverted from other crops and livestock. Only a quarter of the extra animal protein required by 1985 could be produced domestically if livestock production continued to grow at current slow rates and could not be tripled by policy changes over the plan period.

Import requirements of this magnitude are unlikely since the developing countries had considerable difficulty finding even $3 billion for food imports in 1962. Scarcity would drive food prices up, economic growth would slacken and demand would fall. Not only would real incomes fail to grow as desired but also the rise in food prices would cause severe hardship in the poorer sections of the community.

Of the one billion additional people perhaps 400 million would be employed in agriculture. They would have to seek work in a sector where unemployment and underemployment are already serious, and where pressures of population on scarce resources of arable land in Asia, the Near East and northwestern Africa are already critical. If additional jobs are not created in both agriculture and related industries, many will be unable to find productive work, per capita incomes will fall, economic growth will slow down, social problems will multiply and discontent will grow more intense.

The most immediate and urgent problem may appear to be acceleration of food production in order to prevent widespread famine and starvation, but a sober analysis of the potentials for ex-

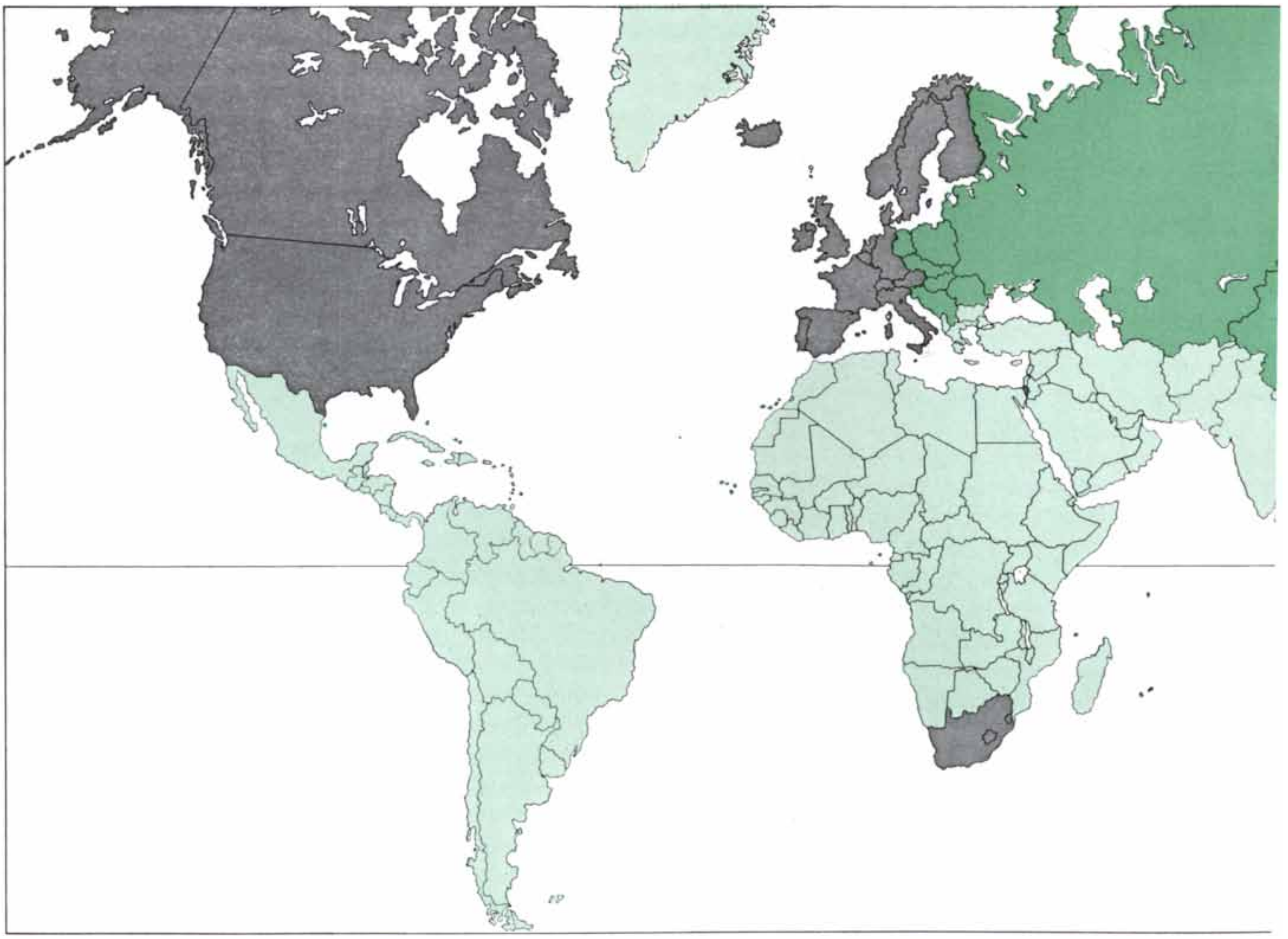
FIELDWORKER bearing a gasoline-powered knapsack sprayer applies weed killer to a rice crop growing in a paddy on an experimental station in the Indian state of Hyderabad. Such stations have been established to develop, test and demonstrate new technology.

panding food output and for providing work for a rapidly increasing number of young people in the developing countries suggests that the latter may prove the more intractable problem. The crucial dilemma may lie in the fact that the very measures that might raise productivity and economic growth most rapidly both in agriculture and in many industries could lead as well to a reduction rather than an increase in requirements for human labor. The creation of jobs does not have the emotional appeal of the face of a hungry child, but unless the problem of employment is given priority equal to that of food supplies the end result could be disastrous.

In view of the alarming trends in supply and demand for food the Organization for Economic Cooperation and Development (OECD) was asked to examine the possibility that the developed countries could produce enough surplus food to meet the major needs of the rest of the world, at least in the short run. The OECD study suggests that a sufficient surplus could in fact be generated, mainly from North America and Oceania, given appropriate measures to bring unutilized land into use. There are, however, important flaws in such a solution. The food would have to be provided at highly subsidized prices if it were to be within the purchasing power of the developing countries. This kind of aid would do nothing to provide employment in the developing regions, and might even tend to discourage efforts to increase agricultural production.

It is obvious that the developing countries must achieve both economic growth and a satisfactory level of income and employment for themselves. They must also plan their population growth instead of letting it happen. The underdeveloped countries are not able, however, to carry out this task unaided, and a heavy burden rests with developed countries to provide adequate and well-coordinated assistance. For high-income countries it is not a question of charity, of duty or of the "white man's burden" but of helping to secure a stable and just society for their own children as much as for those of the developing countries. The plan attempts to show that the providing of aid can be mutually beneficial. An example is the immense market for manufactured products, including those related to agriculture, that expansion of the economy of the developing countries could provide.

A major challenge of the development problem is how to export a greater volume of agricultural products from developing countries to developed ones. The FAO commodity projections indicate that at constant prices exports of agricultural products from developing countries could be expected to grow at only 1.8 percent per year over the period 1962–1975, and probably even less rap-



UNITED NATIONS CLASSIFICATION divides nations into three zones. Zone A consists of market-economy countries such as those of western Europe and North America (*gray*). Zone B countries such as the U.S.S.R. and other nations of eastern Europe have idly during the second decade covered by the Indicative World Plan. This would make it extremely difficult for many of these countries to finance imports of machinery, seed, fertilizer, pesticides and other requisites for economic expansion, let alone massive food imports. The overall economic frame within which the agricultural objectives of the plan have been set would require an annual increase of 3.4 percent in exports, compared with around 2.5 percent over the period 1955–1967. Agricultural imports could be allowed to increase at only 2.8 percent, compared with a past growth of about 5 percent.

This analysis implies that trends toward increased self-sufficiency among the developed countries in many agricultural products must be reversed, and that some of these countries (including those with centrally planned economies) must relax protectionist policies. Here again the Indicative World Plan stresses that this is a question not of benevolence on the part of the developed countries but of economic rationality in terms of an optimum international division of labor. At the same time it must be recognized that bringing about the necessary structural changes in agriculture and industry in those countries may be a long and in some cases painful process. The effort calls for understanding on the part of the developing countries. All nations, both developed and developing, must recognize that there would be no international trade at all if the world were composed entirely of exporters!

On each of these points the Indicative World Plan shows that if present trends continued or were adjusted only through force of circumstances, the results would be quite incompatible with the achievement of the goals that the developing countries have set themselves and that are being embodied in the plans of the UN for the Second Development Decade. The most important purpose of the plan has therefore been to identify the critical sectors and major objectives in agricultural development, and to indicate deliberate policies that would permit more rapid progress toward achieving those objectives.

The Indicative World Plan contains many recommendations designed to achieve the expansion of agriculture needed to provide a firm foundation for accelerated economic growth in the developing world. The objectives considered to be of greatest importance in the light of the problems outlined above are (1) securing staple food supplies, mainly through a faster increase in cereal production, (2) diversifying and improving the quality of the diet, (3) earning and/or saving the foreign exchange crucial to overall development, (4) providing additional employment in agriculture and related industries and (5) increasing productivity through more intensive use of physical resources and modern agricultural technology.

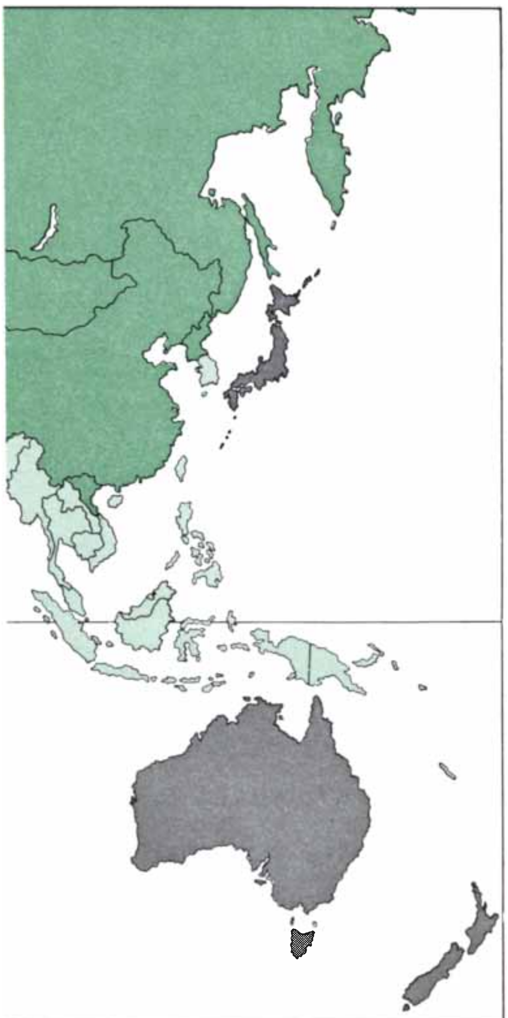
Cereals

Since cereals dominate the cropping pattern of most developing countries and are the main staple for both calories and protein, they have an overwhelming psychological, nutritional and economic importance for farmers and governments. For these reasons planners have devoted a large proportion of technical and financial resources to trying to improve performance in cereal production, with adverse repercussions on technical progress in other food crops and in the livestock sector. Nonetheless, a faster growth rate of cereal production, particularly where population pressure on land is heavy, could eventually free resources to promote other key crops. Faster growth in cereal production, particularly in the second decade of the Indicative World Plan, would then allow a balance to be maintained between supply and the changing pattern of demand. Higher cereal yields are also essential to the massive increase of 80 million tons in concentrate feeds required to meet the plan's livestock objectives. Assurance of the basic cereal supplies must be regarded as the basis for development of other sectors of the economy.

Accordingly the plan calls for a growth of cereal production over the 23 years 1962–1985 of 3.6 percent, compared with around 2.6 percent in the decade 1955–1965. Although this may not appear too formidable a task, it should be noted that the growth of food production, particularly the production of cereals, in Zone C countries fell in all regions except Latin America in the first five years of the 1960's compared with the last five years of the preceding decade. In absolute terms cereal output in the developing countries will have to rise from about 230 million metric tons in 1962 to nearly 520 million tons by 1985 in order to meet the predicted demand for both human consumption and livestock feed.

Until recently a major obstacle to a faster rate of growth of cereal output was the absence of varieties that would give an economic response to the use of modern technology. Determined national and international cooperation, however, has finally resulted in the development of the new high-yield cereal varieties. These varieties are more responsive to irrigation and fertilizers and have a much higher yield ceiling than the varieties formerly available when they are used in combination with pesticides, weed control and other proper farming methods.

These new varieties mature quickly and (in the case of rice) are not strongly season-bound. Two or three harvests can be reaped in a year where the water supply is adequate and there is no serious frost hazard. It is thus technically possible for cereal growers to reduce unit costs by doubling or tripling yields and to obtain the benefits more than once a year. Although the new varieties have been introduced in significant quantities only recently, it is difficult to assess the rate at which their apparently high potential will be reflected in rapidly in-



centrally planned economies (*dark color*). Zone C is developing nations (*light color*).

creasing national average yields. There is nonetheless a sufficient weight of evidence to strongly suggest that a genuine technical breakthrough has been made. For this reason the Indicative World Plan recommends that wider adoption of the new varieties be the driving force of development in the medium term.

It is estimated that these new varieties could be grown on a third of the cereal area in the developing countries by 1985, compared with about 5 percent in 1968. Such widespread planting would, however, require a correspondingly rapid advance in supplies of good seed, fertilizer and pesticides, and in the development of irrigation facilities, better institutions and supporting services and a greatly strengthened research effort. I shall return to these points below.

Protein

The problem of changing the structure and improving the composition of the diet to meet future demand appears to lie essentially with protein supplies rather than with sugars, tubers, fruits and vegetables, a large bulk of which can be produced from a relatively small area of land. Although the Indicative World Plan stresses the need for special measures to produce these crops on a more systematic basis for urban areas, the supply seems comparatively elastic.

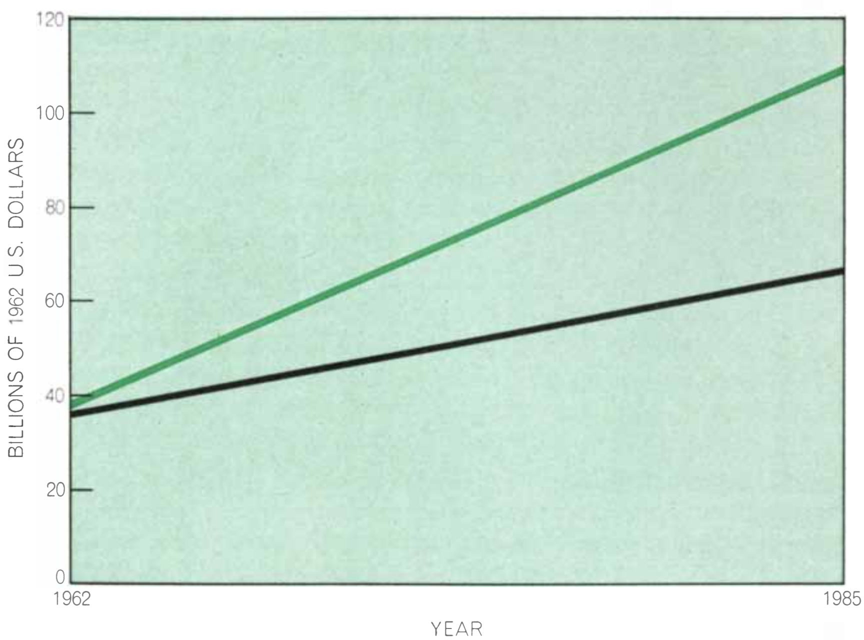
This is not the case for meat and milk from ruminants such as cattle and sheep, which at present provide the bulk of protein of animal origin, and which have a slow potential for expansion because of their long reproductive cycle. Animal production would, in fact, have to advance during the decade 1975–1985 more than twice as fast as in the recent past to reach parity with demand. The alternatives would be either a drastic decrease in per capita intake of animal protein (for example from 14.4 grams per day in the Near East in 1962 to only 9.6 grams per day by 1985) or a massive rise in import requirements.

The oceans have often been regarded as a virtually boundless protein resource. Until some means can be found of utilizing marine plankton and other plants and animals that are not yet exploited, however, such a harvest must be regarded as illusory. The world average increase in the fish catch for 1958–1965 was 7 percent, but a detailed study of the potential of conventional fisheries suggests that only a modest annual increase of 4.7 percent from the 1967 catch level of 60.5 million tons would exhaust the estimated potential of 140 million tons from combined oceanic and inland fisheries by 1985. It is clear that, long before the point of exhaustion was reached, marginal costs would rise sharply to a point where it would no longer be profitable to continue to expand fishing. The sharp drop in the growth of the world fish catch from 8.1 percent per year between 1958 and 1962 to 5.7 percent between 1962 and 1965 may indicate that this point is being reached. The estimated potential of 140 million tons, however, excludes consideration of expanded production from marine culture as well as expanding inland areas under fish culture. The long-run possibilities in these fields are considerable, but the contribution they will be able to make to the total world fish production by 1985 is difficult to predict quantitatively.

Although the Indicative World Plan contains proposals that could improve the fishery prospects toward the end of the plan period, one of the main effects of these recommendations in developed countries would be to reduce costs rather than to increase the catch. At the same time even the implementation of the policies recommended for developing regions, although leading to an increased catch, would not fully satisfy projected food demands in any of the four regions considered. It also seems unlikely that fishes now used for the production of fish meal could fill the protein gap. There are marketing difficulties, including the fact that the areas of greatest fish abundance are often distant from the areas of greatest potential shortage, and problems of consumer preference and taste as well.

Nor could the protein gap be filled, at least on the basis of present technology, solely from vegetable sources. Pulses such as peas, beans and lentils, which are the main sources of high-quality vegetable protein, generally have a very low yield. To suggest that arable land should be used for producing vegetable rather than animal protein in countries with a serious protein deficit ignores both this point and human psychological and dietary preferences.

Because of the inability of any individual sector to meet the full domestic demand for protein by 1985, except in a few countries with a high potential for a special type of product, special priority is given in the Indicative World Plan to a broad-based program to increase protein supplies from all sources more rapidly than has been done in the past. For the immediate future the emphasis is on filling the gap in meat supplies through a rapid expansion of pig and poultry production. This effort should be supplemented by measures to increase the output of vegetable protein through the introduction of leguminous crops in rotation and through improved agricultural practices. Children and other population

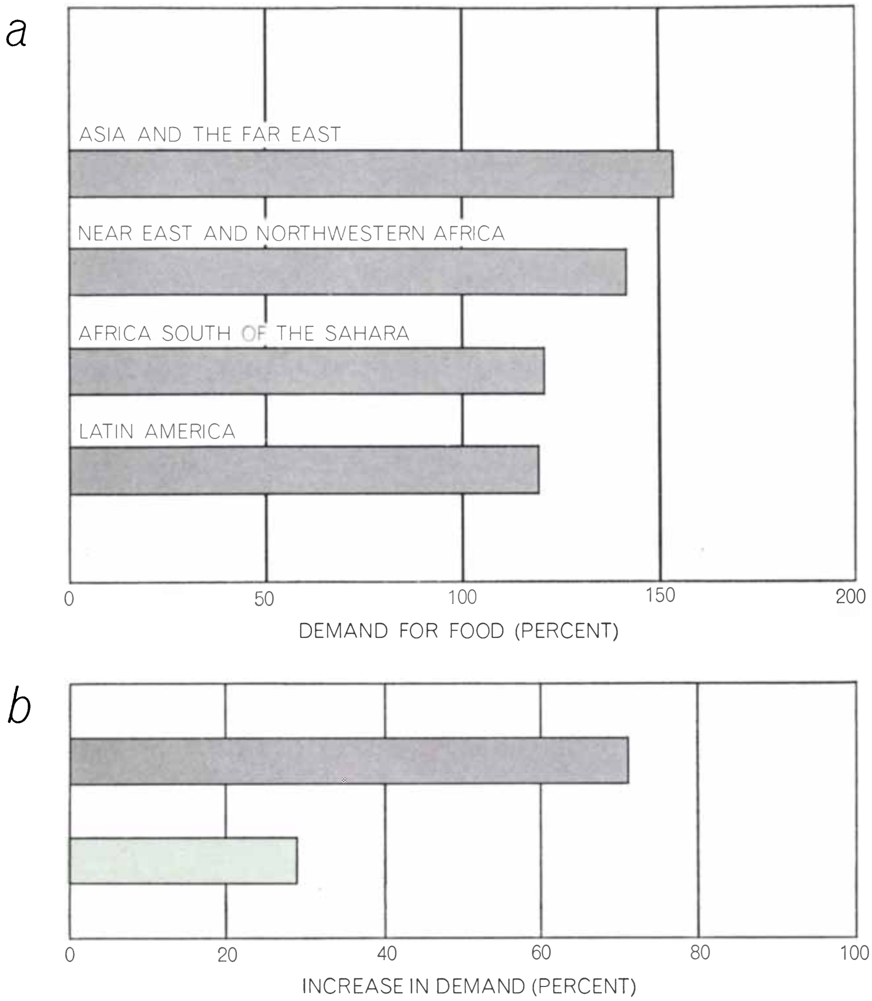


FOOD GAP is caused by demand (*top curve*), measured in 1962 U.S. dollars, which is rising faster than supply (*lower curve*). Unless developing countries increase food production more rapidly than they have, demand for food will exceed supply by about $43 billion in 1985.

groups highly vulnerable to protein malnutrition should be protected by the development of formulated protein-rich foods and the distribution of these carefully designed items and processed milk products. In the more distant future a more varied supply of protein should be provided by the development of higher-yielding varieties of pulses, the buildup of ruminant-livestock inventories, the improvement of ocean-fishing practices and increases in output from inland fisheries. This would meet the projected demand by 1985 except in the case of milk. An average growth of pig and poultry production of between 5 and 10 percent over the entire period of the plan would, however, have to be attained. This formidable goal would have to be achieved largely by industrial methods, in which a key factor would be availability of concentrate feeds at economic prices.

Research will be of vital significance to the success of the entire effort to increase protein supplies. Cereals at present provide some 70 percent of the total available protein, but their content of certain essential amino acids is inadequate for a healthy diet. The development of varieties that would provide a high yield of better-quality protein would be a major breakthrough, as would the production of higher-yielding varieties of protein-rich crops such as peanuts, soya and pulses. Once such improved varieties were developed special efforts would be needed to multiply the seed and distribute it to farmers.

Finally, the Indicative World Plan examines the prospects for bridging the protein gap by the commercial development of new and potentially important protein-manufacturing processes now in the experimental or pilot-project stage. It concludes that such techniques offer exciting long-range possibilities for human nutrition once the problems of translating experimental techniques into large-scale manufacturing processes and overcoming consumer resistance have been solved. In the near future, however, synthetic proteins may prove most useful as components of animal feed, as is now the case with synthetic amino acids. Work on these processes can best be done in the developed countries; meanwhile real and substantial progress in increasing supplies can still be made in the developing countries by more conventional methods.



INCREASED DEMAND FOR FOOD is shown in *a*. By 1985 demand in Asia and Far East will be 154 percent of 1962 level (*top bar*). Demand in Near East and northwestern Africa will exceed 1962 levels by 143 percent (*second from top*). Demand in Africa south of the Sahara will increase by 122 percent (*third*). The demand in Latin America will increase by 120 percent (*fourth*). In *b* top bar represents 71 percent of the total increase caused by population growth; bottom bar represents 29 percent caused by growth in family income.

Financing Agricultural Development

On the basis of the Indicative World Plan proposals, net agricultural exports (valued at constant 1961–1963 average prices) would rise from $6.2 to $14.6 billion, an increase equivalent to an annual growth rate of 3.8 percent. This assumes, however, that (1) agricultural exports from developing countries are allowed better opportunities to compete with products from the rest of the world to the extent that they can achieve comparative economic advantage; (2) both production and processing of agricultural products in developing regions become more efficient, particularly where there is competition from synthetics, and (3) developing countries can exploit opportunities for expanding exports of commodities of high-income elasticity, particularly tropical-forest products and beef. Beef exports of four million tons might be envisioned in South America alone by 1985, compared with one million tons in 1962, if positive steps are taken to eliminate foot-and-mouth disease and suitable agreements are made with importing countries. The plan also argues for a greater share in exports of processed products from developing countries.

A major effort to substitute domestic products for imports at competitive prices is also proposed. Achievement of the cereal and livestock targets alone would save imports worth about $15 billion by 1985 at constant 1962 prices. The domestic market is expected to take over from the export sector in many developing countries as the main driving force toward modernization, increased income and employment in farming. Two factors will generate this trend. One is the growing percentage of the population living in cities; the other is the tremendous growth in food production that is anticipated.

Because of the inadequate data on unemployment and underemployment in agriculture it did not prove possible to propose specific employment targets. The Indicative World Plan has therefore concentrated on an approach to its production objectives that would add to the total man-hours required in agriculture and related occupations. In addition to measures that could add directly to labor requirements within agriculture itself the plan proposes programs to conserve natural resources and to build irrigation structures, roads, rural community centers and other facilities that would help to develop the entire infrastructure basic to economic and social progress. Such programs (which might be supported by food or other aid from developed countries) would thus be aimed at the creation of additional productive capacity and not merely at providing work.

The plan also proposes that agriculture be positively linked to industry. More agricultural products could be processed, and other industries could supply seed, fertilizers, pesticides, machinery, machinery servicing and other necessities.

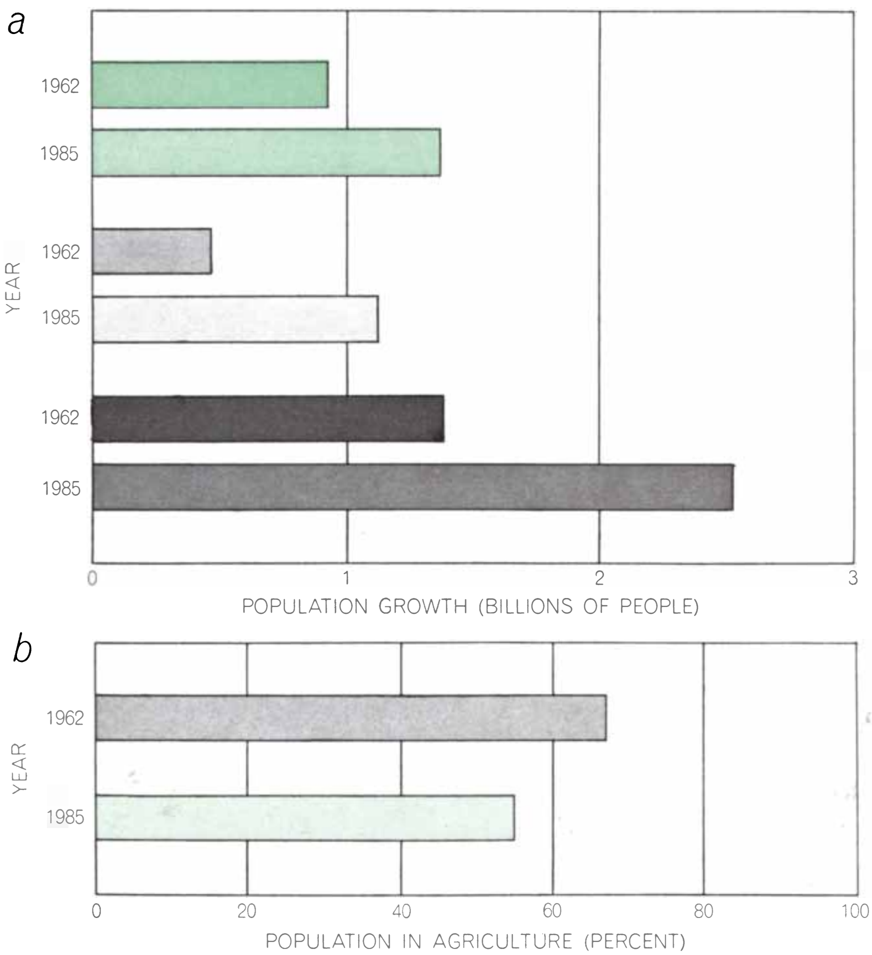
Population

The Indicative World Plan argues for both a faster growth in urban employment and a slower growth of population. No specific measures for family planning are proposed, however; this technology lies outside the sphere of the FAO's activities. It is emphasized that the process of transforming traditional agriculture and increasing employment requires considerable capital expenditure on irrigation, mechanization and other investments, and in addition a massive increase in credit for the purchase of annual cash inputs. More and better-trained technicians for research and other services are also needed. These demands are unlikely to be satisfied in an economic situation where capital accumulation is frustrated by high rates of population growth. Even countries that have large underdeveloped and underpopulated areas must generate most of their capital from within their economy. If an increasing proportion of national resources has to be used to provide the minimum essential infrastructure for an escalating population in settled areas, such capital accumulation will be frustrated. An increasing world population would make it difficult, if not impossible, to solve the problems of agricultural production and employment, not only because there would be more mouths to feed and more jobs to find but also because the mobilization of resources needed for increasing output and labor input through more intensive use of capital resources would become more difficult.

The current low productivity of agriculture in developing regions is reflected in two principal ways. As a result of traditional methods of husbandry, yields per unit of cultivated land are low and so are cropping intensities. Even on irrigated land only one crop may be taken every other year, and in many parts of Africa and Latin America the intervals may be still longer. The traditional farming methods that produce this pattern tend to be associated with the heavy utilization of labor and low utilization of capital resources. Until recently, however, the majority of developing countries have managed to maintain production in line with national requirements by increasing the net area cultivated at the expense of nonarable land (usually pasture and forest). This policy has sometimes led to the permanent destruction of valuable resources for a relatively short-run gain in agricultural output in areas that have proved to be marginal for crops.

An analysis of growth trends in the output of 12 major crops in developed and developing regions makes the point most clearly. In developed countries the cultivated area remained virtually static between 1948 and 1959 and decreased slightly between 1959 and 1966, but the yield per hectare rose by 19 percent in the first period and 18 percent in the second. In contrast the cultivated area in developing regions rose by 21 percent and by 11 percent but yields increased by only 9 percent and 10 percent.

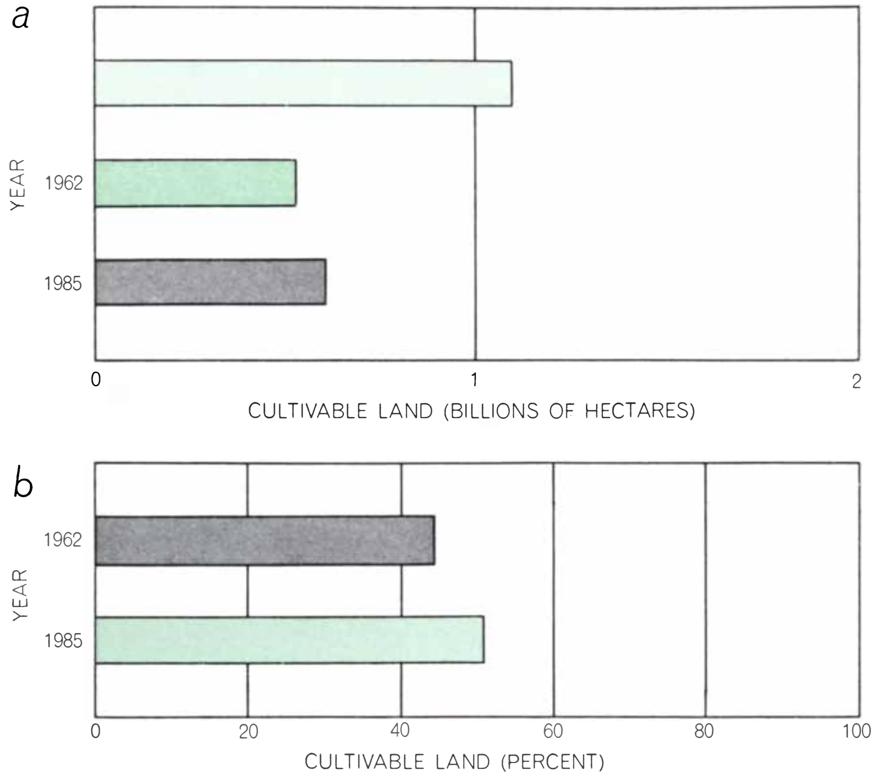
The Indicative World Plan empha-



POPULATION GROWTH in the agricultural sector of undeveloped countries (excluding mainland China), represented by the two bars at the top, will be comparatively modest: from 935 million in 1962 (*dark color*) to almost 1.4 billion by 1985 (*light color*). The two bars in middle show that the nonagricultural population will increase from 460 million in 1962 (*dark gray*) to 1.1 billion by 1985 (*light gray*). The two bars at the bottom show total population of these regions: 1.4 billion in 1962 (*dark gray*) and a projected 2.5 billion by 1985 (*light gray*). In *b* bar at top shows that in 1962, 67 percent of population in these countries was agricultural. Bottom bar shows that by 1985, 55 percent will be agricultural.

sizes that throughout the developing regions good cultivable land is becoming steadily scarcer. Practically the entire potential arable area in South Asia and northwestern Africa will be under the plow by 1985, and a number of countries in the Near East will also be very close to utilizing their full potential. In Central America about 80 percent of the potential arable land will be under cultivation, and a similar situation will probably exist in parts of eastern and central Africa. In all these areas agricultural intensification and the use of modern technology to raise productivity per unit of cultivated land must therefore be regarded as imperative for survival.

Although the ratio of land to man is higher in the rest of Africa south of the Sahara and in South America, cultivation of the apparently large reserves of land in those regions would often mean massive expenditure on jungle clearance, soil conservation and the control of malaria and the tsetse fly. These areas would also have to be populated through migration, and encouraging people to move is a notoriously difficult human problem. The Indicative World Plan has therefore taken the view that better utilization of existing arable land is likely to prove more immediately rewarding in those regions than large-scale opening up of new land. New land would of course still be brought under cultivation during the plan period, but at a slower rate than in the past, and its development would be more carefully scheduled to ensure its optimum use and to prevent waste of resources.



TOTAL CULTIVABLE LAND on the earth, shown in *a*, has an area of 1.1 billion hectares (*top*). In 1962, 512 million hectares were actually in use (*middle*). By 1985, 600 million hectares will be in use (*bottom*). In *b* top bar shows that land cultivated in 1962 is 45 percent of potential. Bottom bar shows that 53 percent of potential area may be in use by 1985.

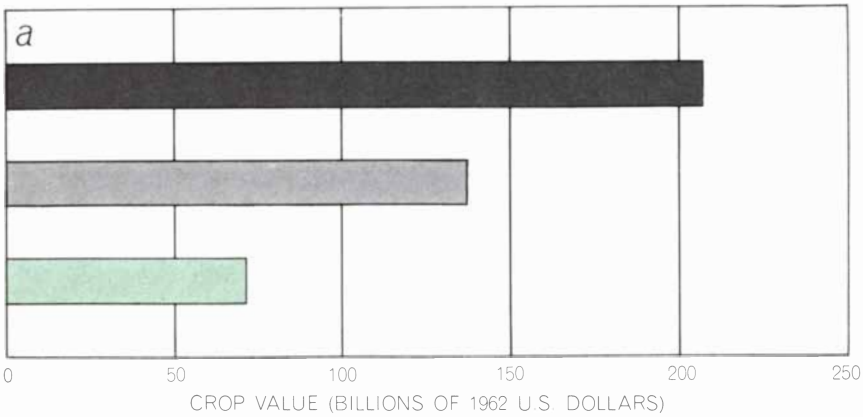
Intensive Agriculture

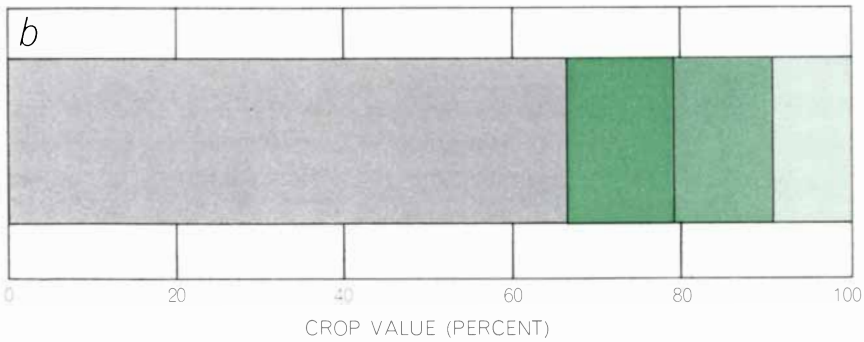
The Indicative World Plan sets out to demonstrate that yields and cropping intensities can be increased, and the plan specifies the measures that will have to be taken to transform traditional methods of farming into the essential modern patterns. It emphasizes that intensive techniques must be applied not only to crops and livestock but also to fisheries and forestry. Emphasis is placed on the need for developed countries to help developing countries modernize their agriculture. Developing countries can also help one another the way Malaysia has helped other countries to improve methods for processing natural rubber.

In spite of some depressing past experiences in attempts to raise yields by introducing the use of modern farming techniques to peasant farmers in developing countries, the plan presents optimistic views concerning the future of cereals and industrial crops. The new cereal varieties and the related technology have been taken up by farmers in much of Asia at an unprecedented rate even if fertilizer and other materials are still not applied in large enough quantities. Farmers have shown themselves willing to respond to price and other incentives provided by governments and are able to utilize the new methods once they are convinced of the benefits. Similar trends are becoming evident around the Mediterranean basin, in Iran and Afghanistan and in parts of Africa. New high-yielding varieties of export crops such as tea, cocoa, rubber, coconut and oil palm have been developed and are being planted in an increasingly large area each year.

In the long run the possibility of increasing cropping intensities may be even more exciting than that of increasing yields. In much of North Africa and the Near East more than half of the arable area lies fallow every year. This situation exists in spite of the fact that ruminant livestock are seriously underfed, that natural grazing lands are under increasingly heavy pressure and that consequently wind and water erode the cropped land and even have damaging repercussions on urban areas. It is proposed that this fallow land be planted with pulses or leguminous fodder crops in areas where the rainfall exceeds 400 millimeters per year. There is strong experimental evidence that the approach is technically feasible and that it could increase income and employment through the introduction of a second crop. Cereal yields would increase and the traditional dichotomy between crop production and livestock production would be mitigated. Pasture yields can also be increased through the use of fertilizers and herbicides and the introduction of improved annual and perennial species of grasses and legumes, both in tropical and in temperate latitudes. Particular weight has been given to these techniques in Latin America.

Multiple-cropping systems can also be introduced in irrigated and tropical areas where moisture and temperature are suitable. Recent research in Asia suggests that this method may be the most potent yet devised for this region of producing maximum output per hectare and of diversifying the crop pattern. These experimental efforts have produced as much as 20 tons of food per hectare per year. In Hong Kong, where multiple cropping is linked to small livestock production, nearly 2,000 man-days





POTENTIAL VALUE of the world's crop production for a typical current year is indicated in *a* by bar at top as being equal to $207 billion. Bar in middle shows that the value of actual harvest is $137 billion. The bar at the bottom shows that difference between actual harvest and potential is $70 billion. In *b* harvest (*gray*) is 66 percent of potential crop. The loss is caused by pests (*dark color*), diseases (*lighter color*) and weeds (*lightest color*).

per hectare can be absorbed to produce a net cash income of $2,000, a high return by developing-country standards. This system offers particular advantages for increasing the production of crops for urban marketing and processing, and thus for the greater market and industrial orientation of production that is an important objective of the plan.

The Indicative World Plan places great weight on expanding the area watered by modern irrigation systems and on investment in flood control and drainage. An assured and controlled water supply allows wider use of high-yielding varieties of annual crops, makes multiple cropping possible and permits the introduction of crops of higher unit value for processing. Particular stress has therefore been laid on irrigation in the main food-deficit regions of Asia, the Near East and northwestern Africa. Between 25 and 30 percent of all the arable area would be irrigated in the first two regions by 1985, and the irrigated harvested area in all the developing countries would almost double over the plan period. Experience has shown that high levels of production depend not merely on efficient irrigation and drainage systems but on an entire "package" of complementary inputs, including of course responsive varieties of crops and breeds of livestock.

Fertilizer

The elimination of weaknesses in research and production services for high-yielding seeds has been given high priority, but the importance of fertilizer has also been stressed. Fertilizer should be used most heavily in the regions where the main irrigation developments are foreseen, such as Asia, the Near East, northwestern Africa and (to a lesser extent) Latin America. An increase in fertilizer production to 28.6 million nutrient tons is envisioned by 1985, compared with an estimated consumption of 2.6 million tons in 1962. This would raise the average fertilizer consumption per hectare harvested for the 64 countries studied from 6.7 kilograms in 1962 to 60 kilograms by 1985.

These various considerations hold the key to initial success in improving yields, but experience in developing countries with relatively high yields and intensive crop rotations suggests that as productivity rises and cropping systems become more complicated a vital component of the production package becomes the protection of crops against losses in the field and in storage. The proposed annual expenditure of $2 billion for crop protection by 1985 is therefore regarded as cheap insurance against losses that were estimated even in 1965 to be $50 billion, an amount roughly equal to the value of the entire proposed increase in crop output required to meet the 1985 targets.

Mechanization also grows increasingly significant over the plan period. Although it is not contended that mechanization is essential to higher crop yields, the more precise cultivation requirements of the new high-yielding cereal varieties, the importance of timely sowing, the elimination of fallow in rain-fed areas and the narrower interval between harvests in more intensive crop rotations argue strongly in its favor. Increased mechanization is not necessarily at variance with a policy of developing labor-intensive agriculture, since the plan proposes a selective strategy that would apply machinery to tasks that could not be done effectively by other means, or that would raise yields or facilitate more intensive land use. The fact is that farming in the developing world is critically underpowered. In 1967 the Science Advisory Committee of the President of the U.S. estimated that the horsepower per capita available from all sources (men, animals and machines) was .05 in Africa, .19 in Asia and .27 in Latin America, compared with a minimum requirement of .5 horsepower for achieving the full agricultural yield potential. In North America about one horsepower is available per capita.

Although the growth rates proposed for mechanization, fertilizers and pesticides are high and would require a major sustained effort, particularly in Africa and Asia, expansion in many developing countries has recently been fast. Fertilizer use has grown with particular rapidity, increasing at a rate of 12 percent per year over the past decade. This trend, together with the possibility of increases in yields and cropping intensities to be attained through advanced technology within the next two decades, gives ground for optimism well beyond the period covered by the plan.

There are, however, no grounds for complacency. If the investments in land and water development are to be recovered and plowed back into the economy, if the costs of the cash inputs essential to modern agriculture are to be recouped by farmers, if the foreign-exchange component of these capital and recurrent costs is to be replaced, and if debt-servicing of foreign financial aid is not to be an insuperable burden, a wide range of supporting actions will have to be initiated in economic, social and institutional fields. Marketing, credit and extension services must be strengthened or even created, manpower must be trained and other institutions must be built. In credit alone a fivefold increase in annual operational lending (from about $8 billion in 1962 to nearly $40 billion by 1985) would be required. Cumulative credit needs for medium- and long-term development are estimated at $86 billion by 1985. In many countries there are no adequate mechanisms either for disbursing and recovering credit at equitable rates or for mobilizing rural savings.

Land Reform

Land reform is likely to be required in all regions, but it has been given special emphasis in many Latin American countries, where much of the land is locked up in underutilized latifundia: large estates descended from the past. Provided that land reform is linked to measures to raise productivity and is not just an abstract slogan, it can not only contribute to a better utilization of resources but also create fresh markets for domestic production through income redistribution and increased purchasing power for the rural population.

Land reform is thus of crucial importance to the Indicative World Plan since the modernization of agricultural techniques and land use is inevitably bound up with the gradual spread of the monetary economy into rural areas. Whereas overall production would rather more than double over the plan period, marketed output is expected to increase between three and four times. The providing of government services therefore needs to be attuned progressively to the rate and direction of the spread of commercialization. The need for government guidance is particularly acute in Africa south of the Sahara, where subsistence production, which is outside the monetary economy, represents a larger share of the total economy than it does in other regions.

Among the many proposals aimed at mobilizing human resources to improve the life of rural populations in the developing countries, the need for providing trained manpower is stressed. Unless action is taken, such manpower may not exist when the need for it is greatest. An acute shortage is foreseen in the supply of intermediate or technical-level personnel for the agricultural services—the people who do the fieldwork. In contrast to this possibility, a potential surplus of university graduates is noted in many countries.

Remedies for these deficiencies will require important decisions at the national level affecting both the future staffing structure of government agricultural services and the related pattern of the agricultural education and training system. Unfortunately it is clear from the regional studies that, whereas almost all countries are actively engaged in agricultural and overall planning, it is comparatively rare for these plans to be related adequately to the trained manpower required to implement them. At a minimum something like 70,000 graduates and 35,000 field-staff people will be needed by 1975 in the countries studied, and 130,000 graduates and 640,000 fieldworkers will be needed by 1985, if lack of trained personnel is not to act as a serious constraint on development.

These estimated manpower require-

OLD WAY of harvesting a crop of wheat is practiced on an experimental farm at Kanganwal in the Punjab. Agricultural worker wearing turban, canvas shoes and light cotton tunic squats so that he can bunch stalks together and then cut them off at the base.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ments may seem high, but they would, on the basis used, amount to only about a quarter of a percent of the predicted agricultural labor force by 1975 and to less than half a percent by 1985. In contrast to these percentages, the proportion of professional and technical workers in the total labor force in most highly developed economies is 5 percent; in the developing countries the technical work force does not exceed 2 percent of the total labor force.

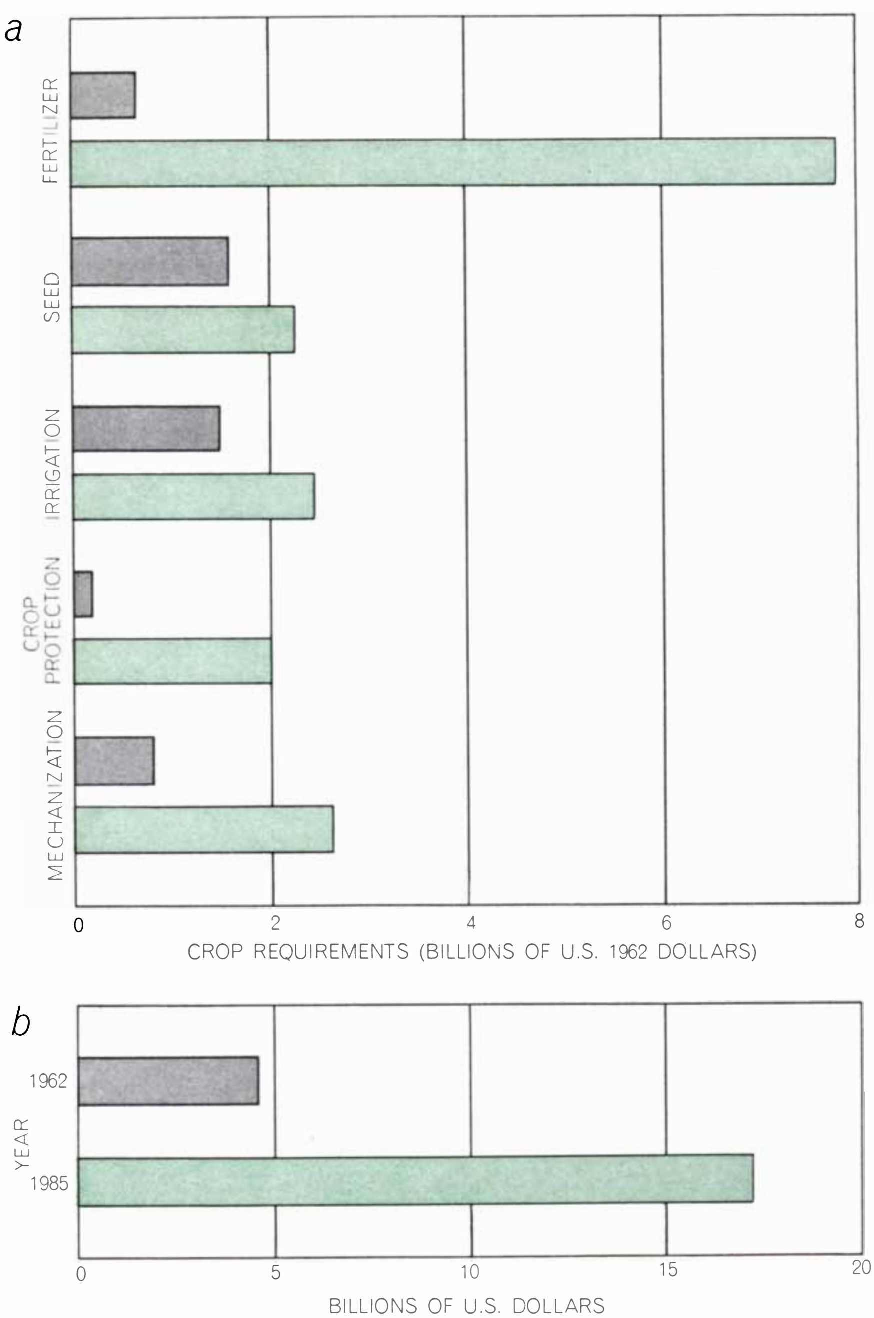
It can be concluded that there is an obvious need for well-thought-out and coordinated manpower and educational strategies in "donor" countries and international agencies as well as in the developing countries if the need for manpower is to be met. Here lies a challenge that the qualified young men and women of the developed countries might welcome provided that they had some assurance their talents could be put to good use within an organized program.

It is perhaps necessary to stress that the Indicative World Plan provides no panacea and proposes no miraculous solutions. It prescribes better planning and a multidisciplinary scientific approach to technical problems, supported by sound institutions and administrative services attuned to the needs of farmers. Even if it contains no startling revelations, the plan has by its very comprehensiveness been able to outline clearly the crucial problems facing world agriculture. By drawing on the wide expertise of a world organization it has also been able to propose fresh solutions and approaches to these problems, and to indicate (often ahead of other contemporary thinking) where and when changes in international or national policies may be required.

The Future

Assuming that the main recommendations contained in the plan could be incorporated into national plans in accordance with local needs and priorities, an average annual increase of about 3.7 percent per year in gross value of agricultural production appears feasible over the next two decades. This would represent a significant improvement over the past decade or so, when production has only just kept up with population growth. It will nevertheless be a difficult task, since the growth rates in both production and trade in the elapsed period of the plan have been rather lower than was anticipated, although there are now encouraging signs of an upward trend in production, particularly in Asia. It is also expected that the growth of the sector will accelerate, from 3.6 percent for the 1962–1975 planning period to 3.9 percent between 1975 and 1985, as constraints on the slower-growing branches of crop and livestock production are reduced by research and as agricultural institutions and services are improved.

The growth rates proposed are to be sustained over a long period and would be difficult to exceed. It follows that for many countries an increase in the gross domestic product of more than 6 percent throughout the period would hardly be feasible, although a faster growth might be possible after 1975. Further work by the FAO in conjunction with other UN agencies in connection with the UN Sec-



CROP INPUTS are represented by pairs of bars. The bar at top indicates that $664 million was spent on fertilizers in 1962 (*gray*). Next bar shows that if the crop-production goals of Indicative World Plan are to be met this expenditure must increase to $7.8 billion by 1985 (*color*). The bars second from top show that expenditure on seed must increase from $1.6 billion (*gray*) to $2.2 billion (*color*). Bars third from top show that expenditure on irrigation must increase from almost $1.5 billion (*gray*) to $2.4 billion (*color*). Bars fourth from top show that expenditures on crop protection must increase from $180 million (*gray*) to $2 billion (*color*). Last pair of bars shows that expenditure on mechanization must increase from $797 million to $2.6 billion. In *b* top bar (*gray*) represents total spent on crop inputs in 1962. Bottom bar shows spending on inputs that will be needed by 1985.

NEW WAY to harvest wheat is practiced on same farm as is shown in picture on page 63. Ox-drawn reaper fells crop with mowing bar while driver pushes cut wheat straws to the side with a pitchfork. The bundles at left are made by workers following the reaper.

ond Development Decade will test the validity of this conclusion. A sustained 6 percent rate of economic growth would, however, be no mean achievement in any country.

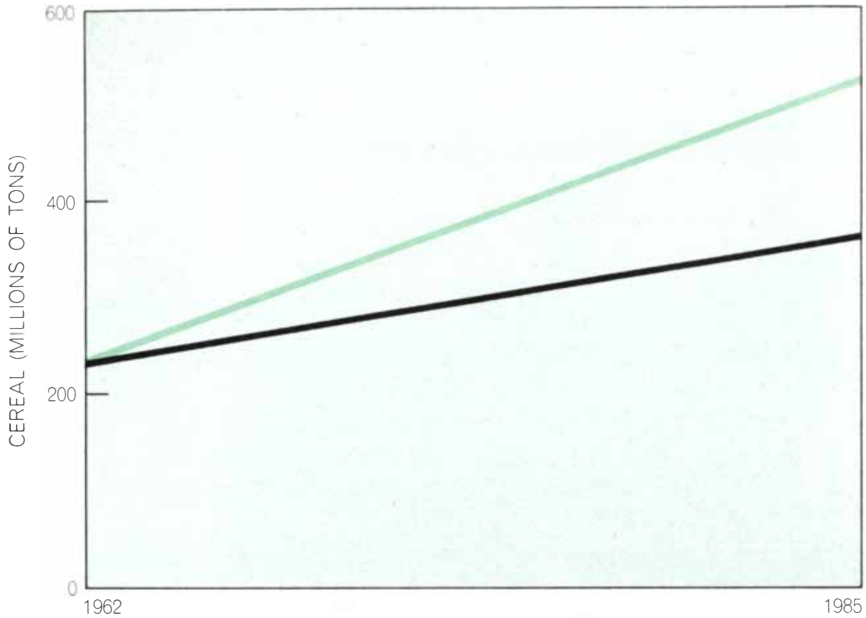
In terms of food supply the "high" alternative proposed in the world study, based on accelerated pig and poultry production, would amount to an increase in net food production retained for domestic consumption of about 3.8 percent per year, compared with only 2.7 percent in the decade prior to 1966. From the nutritional viewpoint calorie supplies (which fell 6 percent short of requirements in the developing countries in the base period) would therefore approximately equal requirements by 1975 and would exceed them by some 10 percent by 1985. Average per capita intake would rise from 2,130 calories in 1962 to 2,480 calories by 1985. This would be a noteworthy advance compared with the ever present specter of famine and malnutrition in the recent past.

A small proportion of the population would nevertheless still be underfed by 1985 as a result of inequalities of income. In the less developed countries protein would be the part of the diet most likely to be scarce. In those areas the staple food tends to provide the bulk of the supply, and the supplementary sources required to improve the quality of the protein in the diet are likely to be relatively expensive. Thus, although the total protein supply would increase from 93.2 to 105.6 percent of nutritional requirements between 1962 and 1985, the situation of low-income groups could even deteriorate if inequalities of distribution are not mitigated and protein sources are not improved.

The best solution to the problem of distribution is employment, and the provisions of the Indicative World Plan should generate many new jobs. A study of the absorptive capacity for labor of the Asian region suggests that requirements for family labor could be raised 15 percent over the plan period in spite of an anticipated increase of 55 percent in the number of farm families by 1985. Gross productivity per day of work would also rise. The combined effects of rising employment and productivity would increase family income by 58 percent. Although these results for an area where the crux of the employment problem appears to lie can be regarded as encouraging, it must be emphasized that they represent only a very preliminary approach by the plan to a problem of vital importance to the future stability of the entire world.

In many respects the conclusions of the Indicative World Plan are optimistic. They show that, given the adoption of the technical, institutional and economic measures proposed, the main problems of hunger and malnutrition could be overcome, trade flows could be improved and a substantial contribution could be made toward providing additional employment. At the same time it must be faced that even if, through the technological measures proposed in the plan, two blades of grass were to be grown where only one grew before, the costs would not be low. Cumulative investments in crops, livestock, forestry and fisheries would total an estimated $112 billion between 1962 and 1985 (of which 42 percent would be for land and water development), plus a further $3 billion for providing the trained workers who would help to implement the proposals. Recurrent annual costs of seed, fertilizer, pesticides and machinery operation—the vital package of inputs—plus the cost of animal-feed supplies would total $26 billion by 1985, more than three times the 1962 level.

The financing of development is therefore likely to be one of the crucial problems of the next two decades. Such financing will largely determine the success or failure of the efforts of the developing countries to achieve self-sustaining growth. Sufficient capital cannot be formed unless a number of conditions prevail. The value of trade in developing countries must grow more rapidly. The private commercial sector must become more deeply involved in the develop-



CEREAL PRODUCTION currently increases at a rate of 2.6 percent per year (*lower curve*). At this rate annual production by 1985 should equal 360 million metric tons. Rate of increase must be raised (*upper curve*) so production by 1985 equals 520 million tons.

ment process, and the internal savings accumulated by the more prosperous farmers must be mobilized. Yet the rapid rise envisioned in inputs and investments, and the comparatively slow expansion of foreign-exchange earnings, imply that the need for financial assistance to developing countries will also rise. Even allowing for the substantial expansion proposed in domestic manufacturing capacity, the annual foreign disbursements on agricultural needs might be of the order of $7 billion by 1985. The developed countries could do much to ease this burden. They could supply these needs on easy terms, provide technical assistance in the establishment of local industries and make other loans for the purchase of plant and equipment. The inclusion of a package of agricultural necessities in aid-financed projects is a further possibility, and this would help in obtaining a more rapid return on capital investments. A number of delegations to the FAO conference, particularly those from the developing countries, considered that higher priority in future planning should be given to this kind of aid and to manufacturing expertise.

In qualitative terms the plan envisions some important changes of emphasis in aid requirements. Food aid, for example, would shift from massive supplies of staple cereals toward high-protein foods (particularly milk products), although "fire brigade" action to supply grains to meet specific emergencies would still be required, and grains would probably form a continuing component of aid in relation to works projects. In determining priorities for such projects the plan stresses the need to develop those that will yield large gains over a short period during the early years in order to achieve the rapid increase in basic food supplies required by 1975.

The need for research is frequently stressed, and it is believed foreign aid could often operate most usefully in assisting the establishment of multidisciplinary research stations to tackle key problems affecting several countries, leaving adaptive research to be undertaken at the national level. There are three research priorities on which international assistance might profitably be focused. The demand is rising more rapidly for such crops as oilseeds, pulses, vegetables and fodders and for ruminant livestock than it is for cereals. Yet the research base from which expansion must come is exceedingly weak, particularly in tropical areas.

Research may also help to increase farm income and employment in areas of lower agricultural yield. A potentially dangerous gap is appearing in several countries between the prosperity in areas where high-yielding varieties can be grown and large responses to inputs can be obtained and the continuing stagnation in poorer regions that are often unirrigated and arid or at high elevations. The Indicative World Plan does not advocate holding back progress in the better areas while solutions are found to this problem (which might in part lie outside agriculture), but it does argue that an additional research effort should be devoted to these poorer regions, possibly supported by social programs to provide work and alleviate distress.

The relatively unsophisticated farmers in the developing countries must be provided with safe, effective and economic pesticides that neither present high short-term toxic hazards nor pollute the environment by accumulating over many years. In many respects the adoption of the plan's proposals would contribute greatly to the conservation of natural resources, but it would also result in a greatly increased use of agricultural chemicals. In view of the widespread alarm over DDT in the U.S. and some other developed countries, it is necessary to put the matter into perspective by emphasizing that even if the plan's recommendations were adopted in full, levels of use per hectare cultivated in the developing countries would by 1985 still be well below the 1965 levels in much of the developed world. To put a brake on technical progress and risk widespread famine cannot be contemplated. A calculated short-run risk must be taken on the continued use of existing chemicals in developing countries at the relatively low levels proposed, while research is redoubled in the developed countries to provide suitable alternatives. The potential size of the commercial market should in itself provide an adequate incentive for such research.

With respect both to research and to extension services the emphasis would be increasingly on training trainers so as to enable technical assistance in such fields to be tapered off gradually. Technical assistance will be completed, however, only when training and research institutions in the developing world are self-supporting. In view of the large increases in trained personnel proposed in the plan this goal is clearly still a long way off. Generally it is recommended that aid should be given more on a team basis and less on an individual basis, with effort spread more evenly between the technology and the economics of production. Nevertheless, there will still be certain fields such as processing (including seed technology) and storage in tropical areas where expertise is limited and individual advice could make a valuable contribution.

The task of national and international planning would be considerably easier if statistics were better, if more evidence could be gathered on levels of nutrition as a result of food-consumption surveys

GUARD armed with rifle protects stand of high-yield wheat on an experimental station in India. Without protection the plot might be raided by farmers who want new seed. High-yielding seed has also appeared in black-market trading in some developing nations.

and if physical resources and their potential could be more accurately assessed. Additional technical assistance would be fruitful in all these fields as an essential basis for planning and policy-making.

In the wider sense international assistance could help developing countries to establish agricultural services that would cater more adequately to such needs, and that might eventually lead to a more uniform approach to both short-term and long-term planning. This could be beneficial both to national planners and to continuing work on global-perspective planning by international agencies. It would also facilitate the continuous evaluation of world-agricultural progress that would permit the establishment of "early warning" systems to alert the world to threatened crises in the fields of production, aid and trade. Clearly such matters require a close and continuing discussion among international, regional and national planners. My own hope is that the FAO's Indicative World Plan will act as a catalyst in this respect.

FETISH was set up to protect two acres of IR-8 high-yield rice growing on a farm in Coimbatore in southern India. An extension worker, at right in dark pants, discusses care of the crop with two field hands, while farmer, dressed in white cotton, looks on.

FREE RADICALS IN BIOLOGICAL SYSTEMS

Short-lived and highly reactive, free radicals are essential intermediates in many chemical processes. In living systems radicals play important roles in radiation damage and in aging

by William A. Pryor

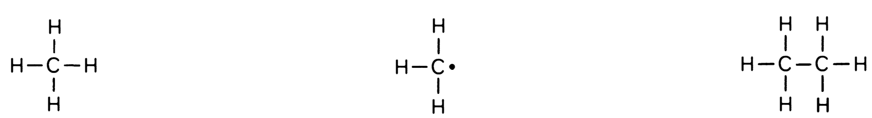
In early 1969 an exquisite creature named Vanessa showed a mouse called Mimi to Simon Templar, hero of the television program "The Saint." Vanessa explained that the mouse's life expectancy had been increased by more than 40 percent as the result of an experiment conducted by Vanessa's father: he had fed Mimi a diet including "butylated hydroxytoluene," or BHT. The episode was actually based on a scientific report: Denham Harman of the University of Nebraska has found that BHT and several other chemicals of widely varying types appear to increase the average life-span of laboratory animals [see "Science and the Citizen," SCIENTIFIC AMERICAN, March, 1969]. The most obvious similarity among these life-lengthening chemicals is that they all interfere with or entirely stop the reactions of ephemeral chemical entities called free radicals.

A free radical is a chemical compound that has an odd number of electrons and is therefore generally highly reactive and unstable and cannot be isolated by ordinary methods. In contrast, most chemical compounds have an even number of electrons and are stable. As we shall see, chemical bonds are made up of a pair of electrons, and the high reactivity of free radicals stems directly from the fact that they have an odd electron. Any species with an odd electron seeks another odd-electron species, and the two proceed to pair their odd electrons to unite and form a bond.

Free radicals are known to be key intermediates in many laboratory, industrial and biochemical processes. Most of the reactions of oxygen involve free radicals, including the slow degradation of organic materials in air, burning and the drying of paints. Many plastics are made by processes that involve free radicals as transient intermediates. Radicals can also be detected in most animal and plant cells, and it is clear that radical chemistry plays a vital role in life processes. Radicals appear to be involved in the production of at least some types of cancer, and the concentration of radicals is different in cancerous cells from what it is in normal cells. Some of the reactions that mediate respiration by living organisms involve radicals. Fats in foods become rancid on oxidation, and so inhibitors of radical reactions, such as BHT, are added to lengthen the storage life of foods. Radiation damage to living systems occurs partly through free radicals. Finally, aging itself has been postulated to involve random destructive reactions by radicals present in the body.

To understand the great reactivity of free radicals it is necessary to understand first why electrons pair to form the normal two-electron bond. Electrons have a magnetic moment and are small magnets; as such they can be considered to have the property termed spin, which can be either "pointing up" or "pointing down" for any electron. Chemical compounds are assigned a "multiplicity" depending on the arrangement of the spins of their electrons. If a molecule has an even number of electrons entirely arranged in pairs with opposed spins, the molecular species is said to be a singlet. If a molecule has an odd number of electrons, then the odd electron must have an unpaired spin; the molecule is called a doublet and is a radical. If a molecule has an even number of electrons but the electrons of one pair have parallel spins, the species is said to be a triplet. Bonds are formed only between electrons that are paired and have antiparallel spins; clearly, then, most molecules will be singlets.

When an organic molecule containing a normal electron-pair bond is heated above a certain temperature (for example, when a hydrocarbon molecule such as is found in petroleum is heated to a temperature between 700 and 800 degrees Celsius), the weakest bond in the compound breaks and the two fragments fly apart. In this process of bond thermolysis, or thermal bond scission, the two electrons in the bond divide, one going with each fragment. The process can be symbolized as A:B → A• + B•, where AB is an ordinary molecule and the two dots represent the two electrons in the A-B bond that hold the molecule together. A process such as this one, in which the bonding pair of electrons divides symmetrically as the bond breaks, is called homolysis, or homolytic bond scission. The two electrons in the A-B bond must be paired and have antiparallel spins, and so the odd electrons in A• and B• initially must have antiparallel spins. If these two radicals come together again, they can re-form the A-B



METHANE is a simple molecule consisting of a carbon atom bonded to four hydrogen atoms (*left*). The methyl free radical (*center*) lacks one hydrogen. A chemical bond consists of two paired electrons; the methyl radical has an odd electron (*dot*) and so it is highly reactive. Two methyl radicals can combine to form an ethane molecule (*right*).

bond. This bond-making process is extremely fast for almost all radicals, so that radicals exist only in very low concentrations. As soon as their concentrations build up, A• and B• collide with each other more frequently, and stable A-B molecules are produced.

Suppose, however, that the A• and B• radicals have not come from the same A-B molecule. If a random pair of A• and B• radicals collide in solution, the spins of the odd electrons in the two radicals are randomly oriented, and the chance that a pair of radicals that have odd electrons with antiparallel spins will collide will be only one in four. This is the case because the triplet state is three times as probable as the singlet, and three in four of the collisions lead to a triplet multiplicity, which cannot form a bond.

There are two possibilities for these triplet pairs: either one of the electrons could "flip" its spin to the other direction, converting the triplet to a singlet pair so that the A-B bond could form, or diffusion could occur faster than this conversion, and the two radicals would simply separate without reacting. Experimentally it is found that triplet radical pairs usually diffuse apart and do not combine to form a bond. Diffusive separation of a pair of radicals occurs in solvents of ordinary viscosity in a time period of only about 10^{-10} second; apparently the triplet-to-singlet conversion requires more time than that. In summary, an A-B molecule will be re-formed every time A• and B• radicals with antiparallel spins encounter each other in solution. However, A• and B• radicals that do not have correlated spins will re-form A-B only one time in four; three in four of the encounters form triplet pairs of radicals, which cannot form bonds.

Since radicals are extremely reactive substances that normally exist only in very dilute solutions, it is not surprising that most practical radical reactions are chain reactions. Radicals, formed in an initiation phase, react in a cyclic propagation sequence in which a product molecule is produced at the same time that another radical is formed to carry on the chain. The cycle is ended by a termination phase, in which radicals recombine. For example, the reaction of a hydrocarbon with chlorine has a chain length of 1,000 or more: every primary radical produced eventually leads to the formation of 1,000 or more molecules of product.

The chain reaction can be initiated by irradiation with light or X rays, by simply heating the system to a high tem-

FREE RADICALS appear to be implicated in the process of aging and in damage to tissues from radiation. The connection between radiation and aging is demonstrated in these photographs, made by Howard J. Curtis of the Brookhaven National Laboratory, of two groups of 14-month-old mice. Originally there were nine mice in each group. One group received a large but nonlethal dose of radiation as young adults. The untreated mice are healthy (*top*). Of the irradiated mice only three survive (*bottom*) and they are senile and gray.

INITIATION

$$a \quad Cl{-}Cl \xrightarrow{\text{LIGHT}} 2\,Cl\bullet$$

$$b \quad \text{INITIATOR} \xrightarrow{\text{HEAT}} R\bullet$$

$$R\bullet + Cl_2 \longrightarrow R{-}Cl + Cl\bullet$$

PROPAGATION

$$c \quad Cl\bullet + CH_4 \longrightarrow HCl + \dot{C}H_3$$

$$d \quad \dot{C}H_3 + Cl_2 \longrightarrow Cl{-}CH_3 + Cl\bullet$$

$$\text{SUM} \quad CH_4 + Cl_2 \longrightarrow Cl{-}CH_3 + HCl$$

TERMINATION

$$2\,Cl\bullet \longrightarrow Cl_2$$

$$Cl\bullet + CH_3\bullet \longrightarrow Cl{-}CH_3$$

$$2CH_3\bullet \longrightarrow CH_3{-}CH_3$$

SIMPLE CHAIN PROCESS, the chlorination of methane, begins with an initiation step in which chlorine atoms (free radicals) are produced (*a*) by light, which dissociates chlorine molecules, or (*b*) by other free radicals (*R•*) provided by the decomposition of a chemical initiator. Two propagation steps (*c, d*) make up the chain sequence, during which the number of radicals is conserved; the steps can be summed to give the overall chemical change. The chain reaction can be terminated by the coupling of any two radicals. A propagation reaction such as *c* or *d*, involving the transfer of an atom from a molecule to a radical, is an atom abstraction, one of the two common types of free-radical propagation reactions.

perature or by the use of an "initiator," a compound with an unusually weak bond that breaks to form radicals at a convenient temperature. The cracking of petroleum is initiated by the scission of one of the carbon-carbon bonds in the petroleum hydrocarbon molecules themselves. A simple hydrocarbon such as ethane has a carbon-carbon bond with a bond strength of 85 kilocalories per mole. The rate of breaking of such a bond becomes appreciable only at temperatures near 700 degrees C. The compounds called peroxides, on the other hand, contain the oxygen-oxygen bond, which is unusually weak. For example, the bond-dissociation energy of the central bond in hydrogen peroxide, HO—OH, is 48 kilocalories per mole. Different organic peroxides dissociate at temperatures ranging from 50 to 200 degrees, so that one can generally find a commercially available peroxide initiator that decomposes to produce radicals at a convenient rate at any desired temperature.

The decomposition of an initiator is not always as simple a process in solution as it is in the gas phase. In the gas phase the A• and B• fragments fly apart and each A-B molecule yields two radicals. In solution, however, it is often observed that each initiator does not produce the two free-radical fragments expected. The reason is that when an initiator undergoes bond scission in solution, the A• and B• fragments are held together very briefly by the "cage" of surrounding solvent molecules. The two fragments strike these solvent molecules as they try to separate and are reflected back toward each other. Consider the decomposition of an azo compound of the type R—N=N—R, which decomposes by splitting out a nitrogen molecule, N≡N, and forming two R• radicals. Since these two radicals have opposed spins and can immediately couple, the formation of the stable molecule R—R in the cage can compete with the diffusion apart of the two R• radicals. This reduces the number of free R• radicals that can initiate chemical reactions, and azo initiators therefore range from about 50 to 100 percent in efficiency.

One of the striking features of radical reactions is that only two general types of propagation reaction are commonly observed: atom abstraction and addition. In the abstraction reaction a free radical attacks another molecule to pull off an atom with one valence electron, usually a hydrogen atom. This reaction can be symbolized as $M\bullet + RH \rightarrow MH + R\bullet$, where M• is any free radical and RH is any hydrogen-containing molecule. Notice that in this reaction, as in all propagation reactions of radicals, the number of radicals is not reduced; one radical is used and another is made.

In the addition reaction a radical adds to a material that contains a double bond: $M\bullet + CH_2{=}CHR \rightarrow M{-}CH_2{-}\dot{C}HR$. Notice that two of the electrons in the double bond unpair; one joins with the odd electron of the free radical to form a new bond and one becomes localized on the adjacent carbon atom to form a new radical center. Materials such as polyethylene, polyvinyl chloride and polystyrene are produced by processes that involve this reaction. A monomer such as ethylene, vinyl chloride or styrene is mixed with an initiator and the mixture is heated to a temperature at which the initiator decomposes to form free radicals [*see bottom illustration at left*].

A dramatic advance in the study of radical reactions was made in 1945 with the invention of an instrument that detects and identifies radicals by the magnetic properties of their odd electron. In this technique, called electron-spin resonance, or ESR, a strong magnetic field is applied to the sample and the energy absorption is measured when the odd electrons flip their spins from being aligned in the same direction as the field to being aligned in the opposite direction. The

INITIATION

$$CH_2{=}CH_2 \xrightarrow{\text{HOT AIR AND HIGH PRESSURE}} ROO\bullet$$

$$ROO\bullet + CH_2{=}CH_2 \longrightarrow ROO{-}CH_2{-}\dot{C}H_2$$

PROPAGATION

$$ROO{-}(CH_2{-}CH_2)_n{-}CH_2{-}\dot{C}H_2 + CH_2{=}CH_2 \longrightarrow ROO{-}(CH_2{-}CH_2)_n{-}CH_2{-}CH_2{-}CH_2{-}\dot{C}H_2$$

TERMINATION

$$ROO{-}(CH_2{-}CH_2)_n{-}CH_2{-}\dot{C}H_2 + ROO\bullet \longrightarrow ROO{-}(CH_2{-}CH_2)_n{-}CH_2{-}CH_2{-}OOR$$

ADDITION REACTION is another common free-radical propagation reaction. In it a radical adds to a compound containing a double bond. For example, polyethylene is made from ethylene by using air as an initiator. The air oxidizes the ethylene to produce peroxide radicals (*ROO•*), which initiate the polymerization (molecular chain-building) process.

amplitude of the resulting energy peaks and the field strengths at which they occur give information on the concentration of radicals and their nature. Often, particularly if the radicals can be studied either in the liquid phase or in a single crystal, the detailed structure of the radical can be identified from its ESR spectrum. This technique has had great impact on the study of radicals in biochemical systems and in tissues, since the radicals can be studied even when the chemistry of the system is incompletely understood.

A living organism is a machine that requires vast amounts of energy for the chemical and physical work it must perform. Organisms obtain their energy by the oxidation of biological materials—by burning food as fuel. The burning does not proceed in the random and inefficient way it would in a furnace; rather, enzymes act as catalysts and the oxidations take place in a controlled sequence of small steps in which more nearly the maximum obtainable energy is liberated.

Oxidation is defined as the loss of electrons; the reverse process, reduction, is the gaining of electrons. Oxidation can proceed through loss of electrons from a substance either in pairs or one at a time. For example, a reaction in which a substance is oxidized by the overall loss of two electrons to form a stable product might occur in one step, in which both electrons are transferred, or in two steps, by the transfer of one electron at a time with a free radical as a transient intermediate. If this intermediate were very unstable, it would rapidly lose the second electron to form the ultimate product and would exist only at extremely low concentrations and be very difficult or even impossible to detect. The difference between oxidations that involve radicals and proceed one electron at a time and those that proceed in two-electron steps is therefore not always obvious just from the products that are formed.

In the early 1930's Leonor Michaelis of the Rockefeller Institute initiated a series of investigations to prove that biological oxidations might involve free radicals. In 1946 he published his highly provocative statement that "all oxidations of organic molecules, although they are bivalent, proceed in two successive univalent [one-electron] steps, the intermediate being a free radical." We now know that this theory is incorrect: there are two-electron oxidations in biochemistry that proceed pairwise and do not involve radicals as intermediates. Nevertheless, Michaelis' views inspired research that is continuing today, providing insight into the nature of the processes by which living organisms obtain energy. Studies by numerous workers in the 1940's and 1950's indicated that an intermediate could sometimes be identified in enzymatic oxidation-reduction reactions of biological molecules, but in spite of Michaelis' conviction there was no proof that the intermediate was a free radical. Starting in 1954, however, and using the newly developed techniques of ESR, Barry Commoner and George E. Pake of Washington University, Helmut Beinert of the University of Wisconsin, Anders Ehrenberg of the Nobel Institute of Sweden and others were able to show that a paramagnetic intermediate can be detected in some enzyme-substrate systems. Commoner in 1956, Melvin Calvin in 1957 and later other investigators showed that ESR signals are produced in plant systems during photosynthesis.

Early ESR instruments were insensitive. They could detect radicals only in biological materials that had been freeze-dried, killing most living systems, and so it was difficult to correlate concentrations of radicals with biological activity. The possibility existed that the radicals being detected were artifacts not directly involved in the biochemical reactions under investigation. Because water absorbs microwave energy very near the frequency used for most commercial ESR instruments, it was particularly difficult to study biological samples in aqueous solution in their natural state.

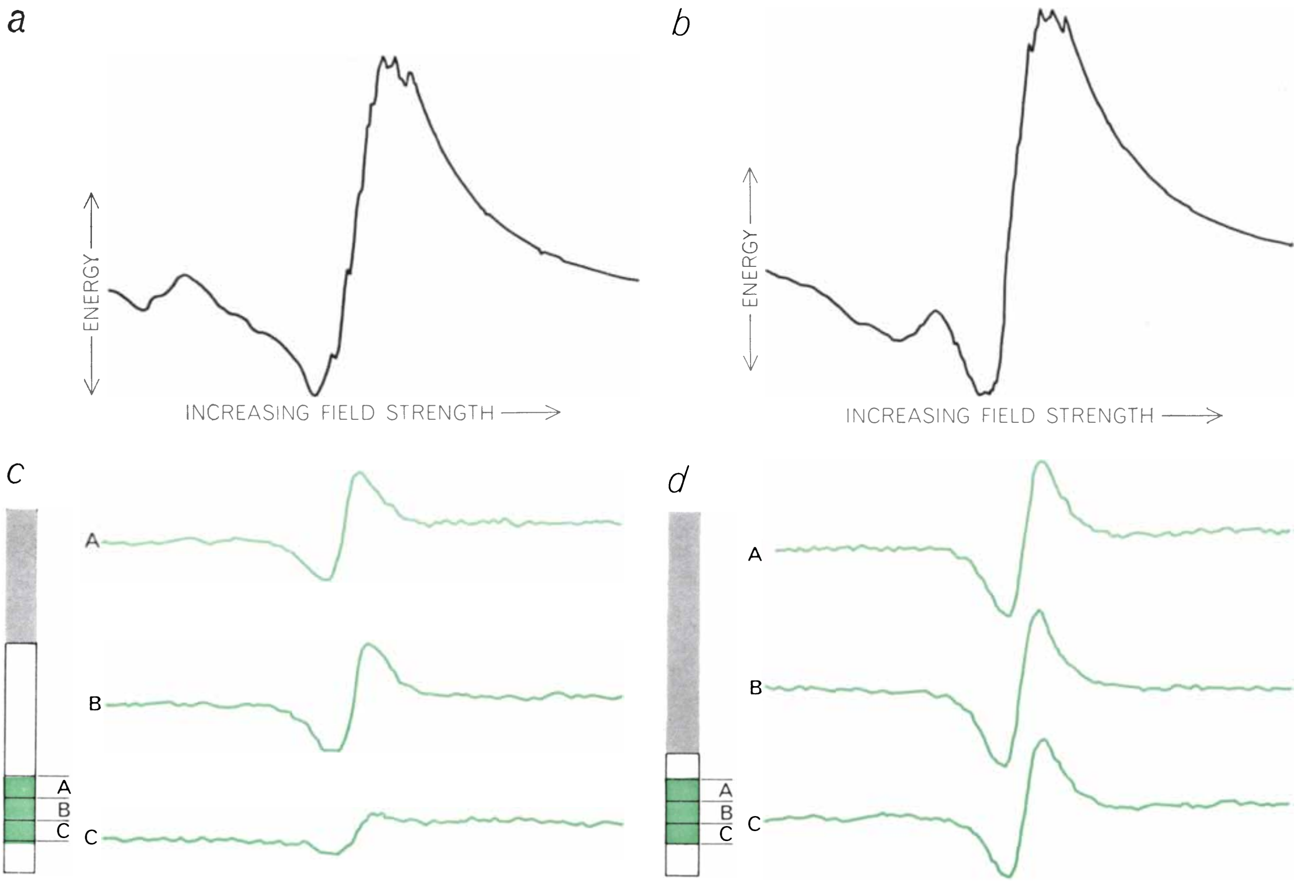
Around 1957 various workers developed new ESR methods that made it possible to study aqueous samples, and as the ESR instruments have improved so has the observed correlation between radical concentration and biological activity. It now appears that radicals are important intermediates in a number of biological processes. In some systems a correlation between biological activity and the concentration of radicals can be established, in others the structure of the radicals can be identified and in still others the rate of reaction of the radicals can be followed. To date, however, all three of these things have been done for very few systems. Two areas in which ESR techniques have been successfully applied are enzymatic oxidations and the mechanisms by which radiation damages organic materials.

Enzymatic oxidations usually proceed through the removal of electrons from the substrate by an enzyme and their transfer to a coenzyme. These are steps in an elaborate electron-transport system that carries the electrons from the substrate to oxygen and effects the reduction of oxygen to water, and they occur in the cigar-shaped organelles of the cell called mitochondria. It is probable that all living cells contain some radicals, but ESR signals can be detected only in certain cells. In general stronger signals are detected in cells with high concentrations of mitochondria. The greatest success in correlating ESR signals with biological activity has come from studies of the flavin coenzymes and coenzyme Q. Several workers have shown that relatively stable radicals are formed in these enzyme systems and that radicals are directly involved as intermediates in the oxidations.

Although most enzymes do not transfer electrons from the substrate directly to oxygen, the oxidases and some of the flavins are able to do so. They generally

PEROXIDE	STRUCTURE	TEMPERATURE (DEGREES CELSIUS)
t-BUTYL HYDROPEROXIDE	$(CH_3)_3CO-OH$	172
CUMENE HYDROPEROXIDE	$C_6H_5C(CH_3)_2O-OH$	158
t-BUTYL PEROXIDE	$(CH_3)_3CO-OC(CH_3)_3$	127
t-BUTYL PERBENZOATE	$C_6H_5CO_2-OC(CH_3)_3$	105
t-BUTYL PERACETATE	$CH_3CO_2-OC(CH_3)_3$	100
BENZOYL PEROXIDE	$C_6H_5CO_2-O_2CC_6H_5$	76
ACETYL PEROXIDE	$CH_3CO_2-O_2CCH_3$	67
t-BUTYL PHENYLPERACETATE	$C_6H_5CH_2CO_2-OC(CH_3)_3$	66
t-BUTYL TRIPHENYLPERACETATE	$(C_6H_5)_3CCO_2-OC(CH_3)_3$	11

INITIATORS can be selected from among a number of organic compounds that dissociate to produce free radicals at a wide range of temperatures. Most such compounds are peroxides, which contain the readily broken oxygen-oxygen bond. The table lists some peroxide initiators and gives the temperature at which each of them has a half-life of 10 hours.



ELECTRON-SPIN RESONANCE (ESR) detects unpaired electrons and thus measures the number and properties of free radicals in a sample placed in a magnetic field. An ESR curve traces the changes in energy associated with the flipping of electron spins as the magnetic field varies; the amplitude of a peak and its location are characteristic of the concentrations and the chemical sites of free radicals. These ESR spectra from the Japan Electron Optics Company are those of the tobacco in an unsmoked cigarette (*a*) and in a smoked butt (*b*) and of various levels (*A, B and C*) of the filters of half-smoked (*c*) and nine-tenths-smoked (*d*) cigarettes.

reduce oxygen to hydrogen peroxide, which is subsequently reduced to water by another class of enzymes called catalases or peroxidases. Hydrogen peroxide is produced in all cells through the reduction of oxygen, and the peroxidase enzymes are important in keeping peroxide concentrations down to levels that are not damaging to the cell. Lawrence H. Piette of the University of Hawaii and others have shown that peroxidase-substrate systems give ESR signals, and the activity of the enzyme has been correlated with the strength of the signal.

The processes by which radiation interacts with organic materials are quite complex, and we shall consider only the simplest scheme here. Ionizing radiation can consist of electromagnetic radiation such as very-short-wavelength light or X rays, or of highly energetic particles such as high-speed electrons or alpha particles. Radiation causes ionization by knocking electrons away from the molecules to which they belong, thus producing free electrons and positively charged ions, or cation radicals. The ions and electrons may recombine to produce neutral molecules in an excited state, which can undergo homolysis to produce free radicals; radicals can also be produced by reactions between the cation radicals and the neutral molecules.

Cells are from 60 to 80 percent water and when a plant or an animal is irradiated, most of the energy is deposited in the aqueous phase; less often will a primary ionization occur in an organic biomolecule. A portion of the damage to living systems therefore results from reactive particles that are formed in the water phase and diffuse to an organic molecule in the cell, causing secondary reactions. The chief radical species produced in the radiolysis of water and implicated in radiation damage are solvated electrons (electrons associated with water molecules), hydrogen atoms and hydroxyl radicals (HO•).

Cells are extremely sensitive to radiation. Calculations show that radiation that destroys perhaps only one molecule in 100 million can have profound biological consequences and can even kill the cell. The most reasonable explanation of this biological magnification is that the energy from radiation can be transferred to critical polymer molecules in the nucleus of the cell. Aside from certain effects on cellular membranes, which will be discussed later, it is probable that the cell nucleus and its chromosomes are critical in determining radiation sensitivity. About half of the dry mass of the nucleus consists of chromosomes and of this about half is deoxyribonucleic acid (DNA) and about half is associated protein material. Two types of reactions are therefore particularly important in terms of the damage they can cause. The first is the reaction of radicals from water with DNA and the second is their reaction with proteins.

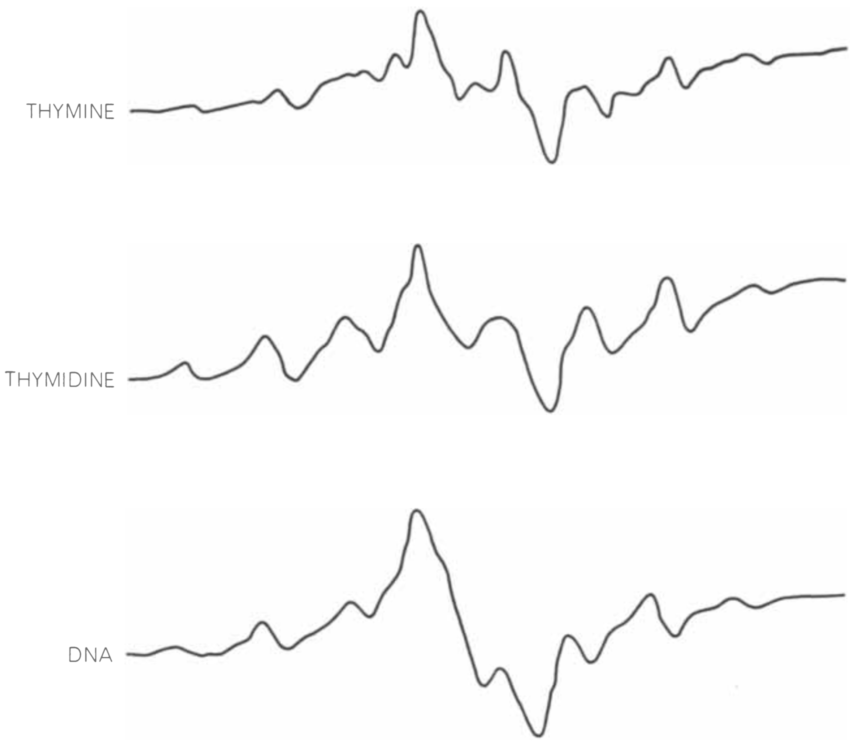
Each strand of the double helix of DNA is a chain of subunits called nucleotides, arranged in an ordered sequence to spell out genetic instructions according to the genetic code. The distinctive element of each nucleotide is one of four nitrogenous bases: thymine, adenine, guanine and cytosine. All three of the radicals produced in water radiolysis react with these bases at a high rate. For example, hydrogen atoms add to thymine to produce a radical that can be identified by its characteristic ESR spectrum. The same spectrum can be observed when hydrogen atoms react with the thymine nucleotide, thymidylic acid, or when either solid DNA or an aqueous solution of DNA is irradiated [*see top illustration at right*]. The thymine radicals are not stable and they react further to alter the DNA molecule and interfere with the coding of genetic information. Such a change could be nonlethal, since the cell has mechanisms for excising and repairing damage to its DNA, but it would be expected to often alter a gene in such a way that it would kill the cell.

Dov Elad and his co-workers at the Weizmann Institute of Science have recently shown that certain organic compounds can add to the bases in DNA. These reactions proceed in the same way whether they are induced by light, high-energy radiation or normal free-radical initiators, and they unquestionably involve free radicals as intermediates.

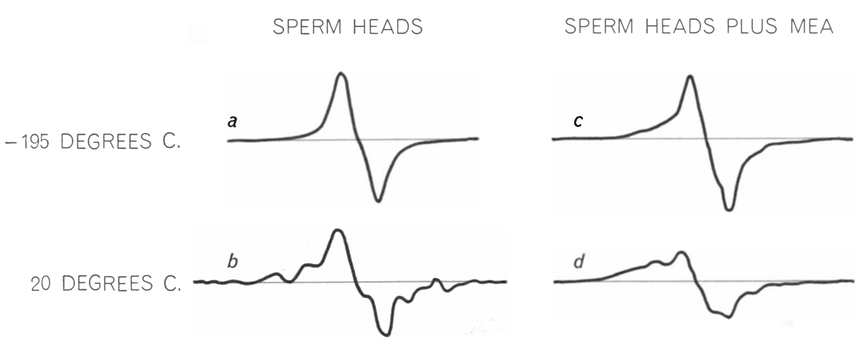
Another reaction that may cause mutations has been identified by H. J. Rhaese of the National Institutes of Health. He has shown that hydrogen peroxide reacts with adenine and modifies its structure. This reaction occurs when adenine is irradiated with X rays or when it is simply treated with hydrogen peroxide and ferric ions, a mixture known to produce hydroxyl radicals. Although it has not yet been established that this slight modification of adenine causes mutations in organisms, there is some evidence that it may contribute to the weak mutagenic effect of X rays. For example, there appears to be a higher incidence of chromosome aberrations in cells with low concentrations of catalase and consequently with higher than normal concentrations of hydrogen peroxide.

Proteins, which play an important role in the chemistry of all plant and animal cells, are made up of many amino acid molecules joined together in a peptide chain. Proteins are held in a particular configuration by molecular forces, and the shape of each protein is critical to its exact functioning. One amino acid, cysteine, contains a sulfur-hydrogen group, and two of these groups can be converted to produce a disulfide bond between two cysteine residues in the protein chain. This S–S link helps to hold the protein molecules in their active configuration. (A macroscopic example of this is the permanent-waving of hair. Hair is made of the protein keratin, which contains disulfide cross-links that help the hair to hold its shape. In permanent-waving these bonds are first reduced to S–H groups; then the molecules are arranged in the desired conformation by rolling the hair on rods and the S–S bonds are then remade by oxidation with peroxide.)

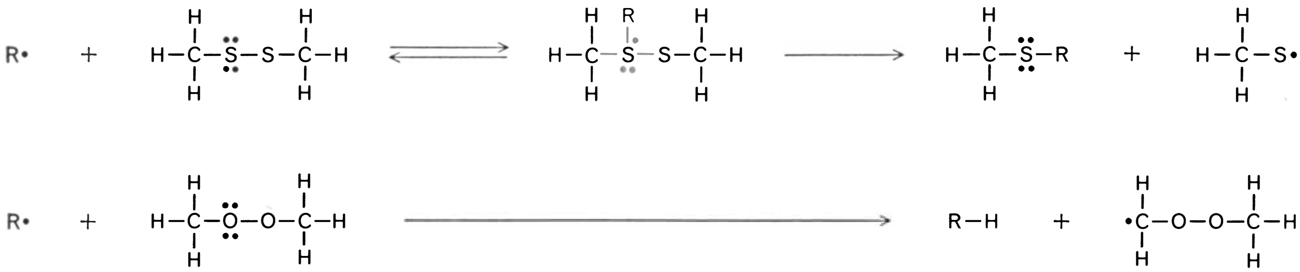
In 1955 Walter Gordy of Duke University examined the ESR spectra of irradiated proteins and proposed that two types of radical are produced. One gives a two-peak spectrum that varies slightly from one protein to another. It is now known that this spectrum results from an odd electron localized on a carbon atom of the peptide-chain backbone. The second type of radical gives an ESR absorption at the low-field end of the spectrum and is easy to identify



THYMINE, one of the four bases in DNA, is sensitive to radiation, probably at least in part because hydrogen atoms add to thymine to form free radicals, which can react to alter the DNA. The top ESR spectrum, from an experiment conducted by Anders Ehrenberg and his colleagues, shows the pattern typical of the radical, produced when thymine was subjected to gamma radiation. The other two spectra show that the same radical is present in thymidine (a part of the DNA molecule that contains thymine) and in a purified DNA sample.



EFFECTS of temperature and of a sulfur-containing drug on radical formation were demonstrated by Peter Alexander. Fish-sperm heads, which are rich in DNA, were cooled to –195 degrees Celsius and irradiated. The frozen sample shows a typical low-temperature spectrum (*a*). When the sample is warmed, the DNA spectrum appears as the radicals become mobile (*b*). Addition of MEA, containing thiol (S—H) groups, has little effect on the frozen sample (*c*). When the sample is warmed, the radicals transfer from DNA to thiols and a new plateau characteristic of sulfur radicals appears at the left in the spectrum (*d*).



SULFUR COMPOUNDS protect against radiation because they react readily with radicals, which attack the sulfur-sulfur bond of disulfides faster than they attack the oxygen-oxygen bond of peroxides, according to the author and his colleagues. It may be that an attack by a radical on methyl disulfide, for example (*top*), can form a relatively stable intermediate because the sulfur atom can accommodate nine electrons (*color*). An attack by a radical on methyl peroxide (*bottom*), on the other hand, cannot involve this path, since the oxygen atom can only accommodate eight electrons. As a result the reaction proceeds by hydrogen abstraction instead.

as a sulfur radical, RS•; it is observed in enzymes that contain S—H or disulfide groups and in mixtures of enzymes with added sulfur compounds. Thormod Henriksen in Norway, Peter Alexander and M. G. Ormerod in England and Harold C. Box and several other workers in this country have shown that irradiation of proteins at low temperatures produces ESR signals of the carbon-radical type, but that heating the material gradually converts at least some of these carbon radicals to sulfur radicals. Clearly protein molecules possess a mechanism for transferring the site of the destruction from one part of the molecule to another or to nearby molecules.

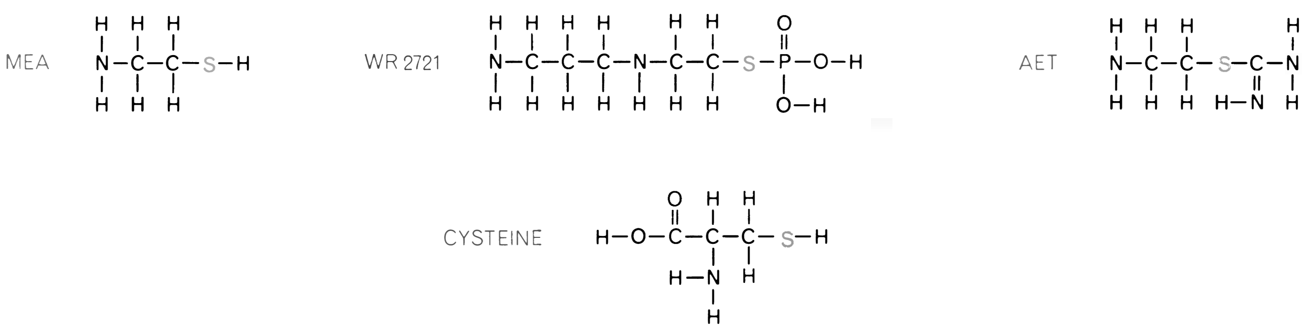
Although the sulfur-sulfur bond is critical in determining the shape of many proteins, it is cleaved remarkably easily. My research group at Louisiana State University has studied the cleavage of the disulfide bond by radicals and we believe it may be faster than analogous reactions of oxygen compounds because of the ability of sulfur to react with radicals to form a relatively stable intermediate [*see illustration above*]. There is evidence from other laboratories that some of the reactions of ions with sulfur-sulfur bonds may also proceed through a related intermediate complex.

Recently several workers in this country, Gabriel Stein in Israel and H. Jung in Germany have shown that the hydrogen atom attacks the sulfur-sulfur bond so efficiently that each hydrogen atom produced in a model system leads to the inactivation of an entire enzyme molecule. Since enzymes are among the largest molecules known and the hydrogen atom is the smallest atom, this is a bit like killing an elephant with a BB pellet. When a cell is irradiated, very few of the hydrogen atoms from the aqueous phase are likely to collide with an enzyme molecule, but apparently those that do can cause the total destruction of the biological activity of the enzyme.

Since sulfur groups react readily with radicals, it is not surprising that sulfur compounds act as drugs that protect against radiation. There are a number of mechanisms by which a molecule might protect a cell from radiation damage. For example, compounds containing S—H groups (thiols) can protect important biological molecules through a repair process. A number of workers have shown that radiation can result in the removal of a hydrogen atom from a biological polymer, leaving a radical. The thiol can then repair this damage by a hydrogen-transfer reaction, donating a hydrogen atom to the polymer radical and creating a less lethal thiyl radical, R—S•. These reactions are thought to be partly responsible for the significant radiation-protection activity of thiols. Most compounds containing S—H or S—S bonds act as protective agents in laboratory systems, but in the body problems of solubility, diffusion and toxicity arise and so only certain sulfur compounds are effective radiation-protection drugs.

It is interesting that the potent radiation-protection drug beta-mercaptoethylamine (MEA), or cysteamine, also has been found by Harman to be effective in lengthening the mean life-span of mice. There are radicals in the body and it is clear that they can damage biochemical systems in cells; radiation involves radical reactions and also effects aging. These facts have suggested to many investigators that aging itself must be at least partly due to damage caused by radical reactions within the body.

In an organism such as man, aging can be expected to result from many chemical reactions, and there is no reason to anticipate a single cause or mechanism. On the contrary, it is likely that several different and perhaps complex mechanisms make significant contributions to the total changes that occur in our bodies



PROTECTION AGAINST RADIATION is afforded by a number of compounds, most of which contain sulfur. The structures of four of the most effective sulfur-containing drugs are shown here: MEA, or cysteamine, WR 2721, AET and the amino acid cysteine.

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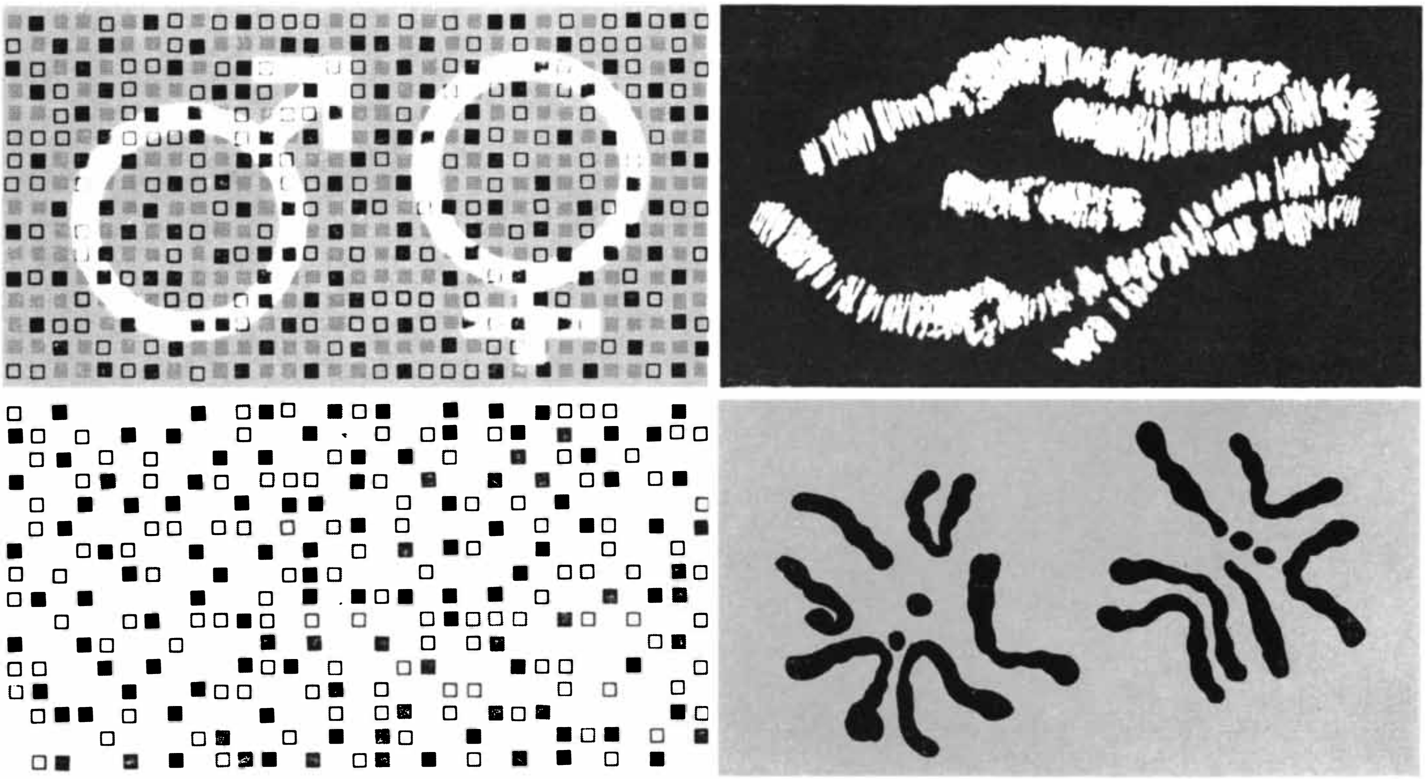

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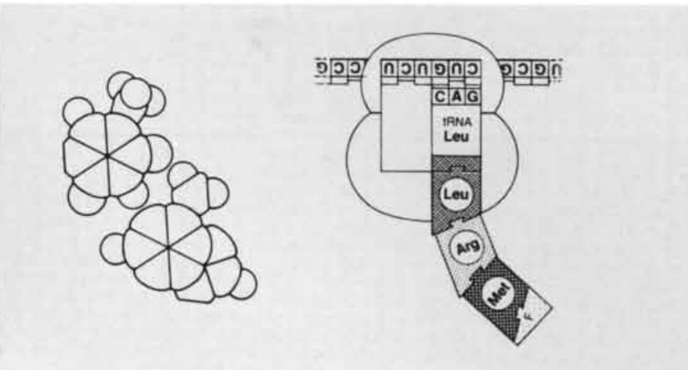

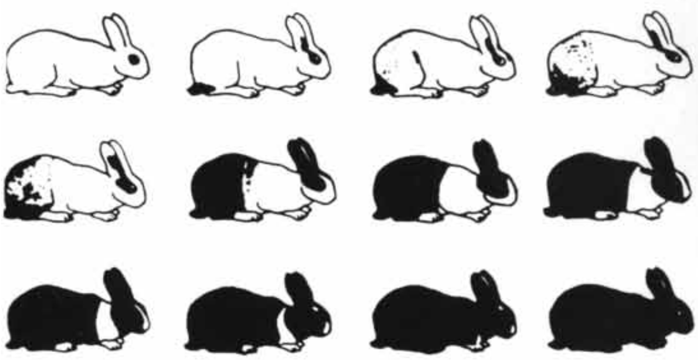

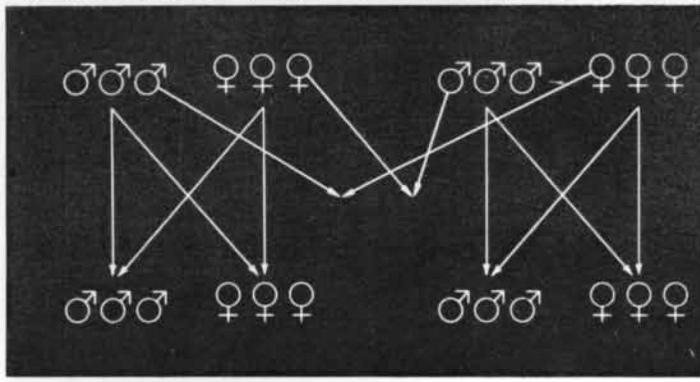

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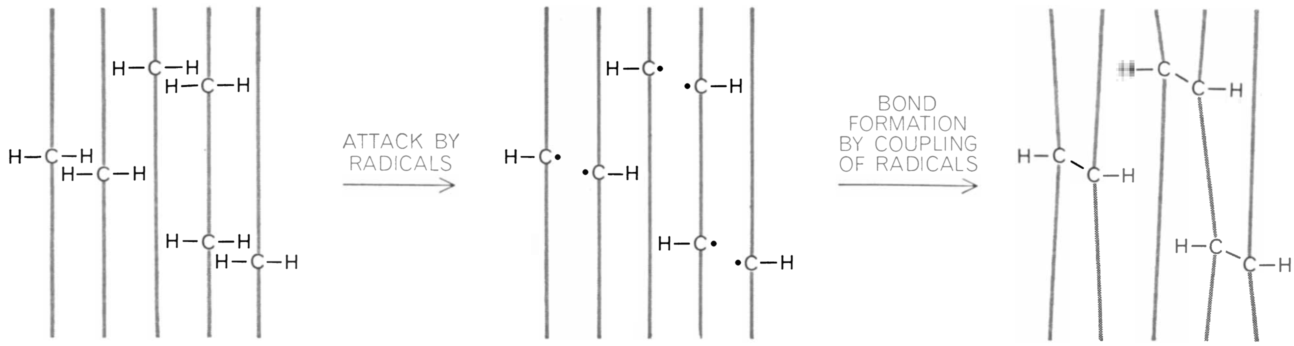
Photograph by hand-held camera aboard Gemini 8 shows thin veil of earth's atmosphere with towering cumulus clouds in silhouette. NASA with time. There is increasing evidence that at least some of these mechanisms involve the reactions of free radicals.

One theory suggests that aging may be partly due to changes in the connective tissues collagen, elastin and reticulin. These are the structural materials of the body, largely protein in composition, that give tissues shape, plasticity, resilience and elasticity. The biological role of collagen depends on its high plasticity and its ability to bear stress and maintain shape and form; it is present throughout the body but it occurs in particularly high concentrations in flexible organs such as the lungs, blood vessels, skin and muscles. With age, collagen fibers become denser, stiffer, thicker and less plastic. They also become insoluble in organic solvents, indicating that they have become cross-linked by chemical bonds. It is not unreasonable to suggest that some of this cross-linking could result from free-radical reactions.

Most collagen occurs in organs with high concentrations of blood serum, in which radicals are known to be present, and ESR studies show that free radicals attack proteins, producing radical centers on the protein chains. It might be expected that the subsequent combination of these protein radicals could sometimes lead to cross-linking between the protein collagen fibers, and thus to stiffness and increased density [*see illustration on next page*]. It may not be the free radicals themselves that cause cross-linking but rather some product of their reactions. It is known that under most conditions radiation does not cross-link collagen but rather stimulates collagen synthesis at an increased rate, producing some of the same symptoms as cross-linking. This is one of the ways in which radiation mimics the effects of aging, as William F. Forbes of the University of Waterloo in Canada has pointed out, rather than truly accelerating natural aging.

A theory favored by Howard J. Curtis of the Brookhaven National Laboratory and others suggests that aging in mammals results from mutations in the animals' somatic cells (the body cells, as distinguished from the germ cells involved in reproduction). The theory is conceptually quite simple: DNA directs the synthesis of ribonucleic acid (RNA), which in turn directs the synthesis of all the proteins produced by the cell. If errors gradually accumulate in the genetic information of the DNA or RNA, the cell begins to malfunction and may die. As in other aging theories,



COLLAGEN, a protein connective tissue, becomes less flexible with age because its fibers become cross-linked. In the speculative scheme shown here the cross-linking is caused by free radicals. Carbon atoms, which for the sake of simplicity are shown here with two hydrogen atoms (*left*), are attacked by radicals; they lose a hydrogen atom, giving rise to radical centers on the peptide chain. Pairs of radical centers could couple with each other, producing cross-links that bind the fibers to one another, stiffening them.

the concept is simple but the proof is not. The DNA molecule is enormously complex and there is no direct chemical evidence that it changes with time. Furthermore, it is not possible to measure mutations in somatic cells directly and indirect techniques must be found. In support of the mutation theory, it has been shown that certain radiation effects on chromosome aberrations and on life expectancy are similar, that short-lived animals develop chromosome aberrations faster than long-lived ones and that mouse strains with a longer lifespan also have a lower sensitivity to radiation. There remain several serious difficulties with this theory, however, and it is not universally accepted.

A theory that aging is due at least in part to the peroxidation of lipids explicitly implicates radical reactions. The lipids, which include the fats, constitute the most concentrated source of energy available to the organism. They are oxidized in the cell, chiefly in the mitochondria, in a series of reactions that normally proceed in carefully controlled enzyme-regulated steps. Like all organic materials, however, lipids can also react with oxygen in a nonenzymatic, free-radical pathway. Those that contain reactive hydrogen atoms called allylic hydrogens are particularly prone to undergo the radical reaction. This type of hydrogen occurs in the polyunsaturated fatty acids, which account for about 13 percent of the caloric intake of the human diet.

The peroxidation of lipids is a typical free-radical chain process involving both hydrogen transfer reactions and addition reactions [*see illustration below*]. The importance of lipid peroxidation to aging rests on the belief that damage to cells accumulated over the lifetime of the organism gradually reduces the efficiency with which the cell carries out its functions. For example, A. L. Tappel of the University of California at Davis has shown that when enzymes are present in systems in which fatty acids are being oxidized, the biological activity of the enzymes is destroyed. The oxygen does not react with the enzymes; rather the enzymes are attacked either by radicals produced through the interaction of the lipids and oxygen or by nonradical molecular products from the oxidation of the fats, or by both. Furthermore, there are numerous similarities between the damage to enzymes produced by lipid peroxidation and the damage from radiation.

The body provides a natural lipid antioxidant in vitamin E, and the products derived from vitamin E show that it functions at least partly as a free-radical inhibitor that is sacrificially oxidized to protect the lipids. It is striking that the effects of diets deficient in vitamin E resemble certain effects of both radiation damage and aging. In all three cases there is evidence for structural damage to various cellular membranes.

The membranes in a cell are the partitions that compartmentalize reaction systems so that they do not interfere with one another. Membranes also appear to contain many of the specific receptor sites for the binding of hormones and drugs. Moreover, they must be permeable to particular chemical species at precisely defined rates. They are therefore highly structured and extremely sensitive components, and any deterioration of a cell's membranes must seriously affect its ability to function and could be responsible for some of the effects of cellular aging. Membranes consist of lipids and proteins in varying proportions; the membranes of mitochondria, for example, are about 27 percent lipid and 73 percent protein. Research in a number of laboratories makes it clear that both radiation and free radicals produce significant structural deterioration in membranes and that peroxidation of lipids leads to products that cause cross-linking, reduced permeability and structural decay in membranes.

A particularly clear case of free-radical damage to membranes has been demonstrated for human red blood cells by Edward M. Kosower of the State University of New York at Stony Brook and his wife Nechama S. Kosower of the Albert Einstein College of Medicine. They used a drug that reacts with glutathione, a thiol in blood cells, inhibiting its protective action. The same drug also produces an intermediate that, under the controlled conditions of their experiments, reacts with oxygen in the cell membrane to form radicals; the radicals cause lipid autoxidation, which destroys the viability of the cell wall and bursts

ABSTRACTION	$P{-}H \xrightarrow{ROO\cdot} P\cdot$	
ADDITION	$P\cdot + O_2 \longrightarrow POO\cdot$	
ABSTRACTION	$P{-}H + POO\cdot \longrightarrow P\cdot + POOH$	

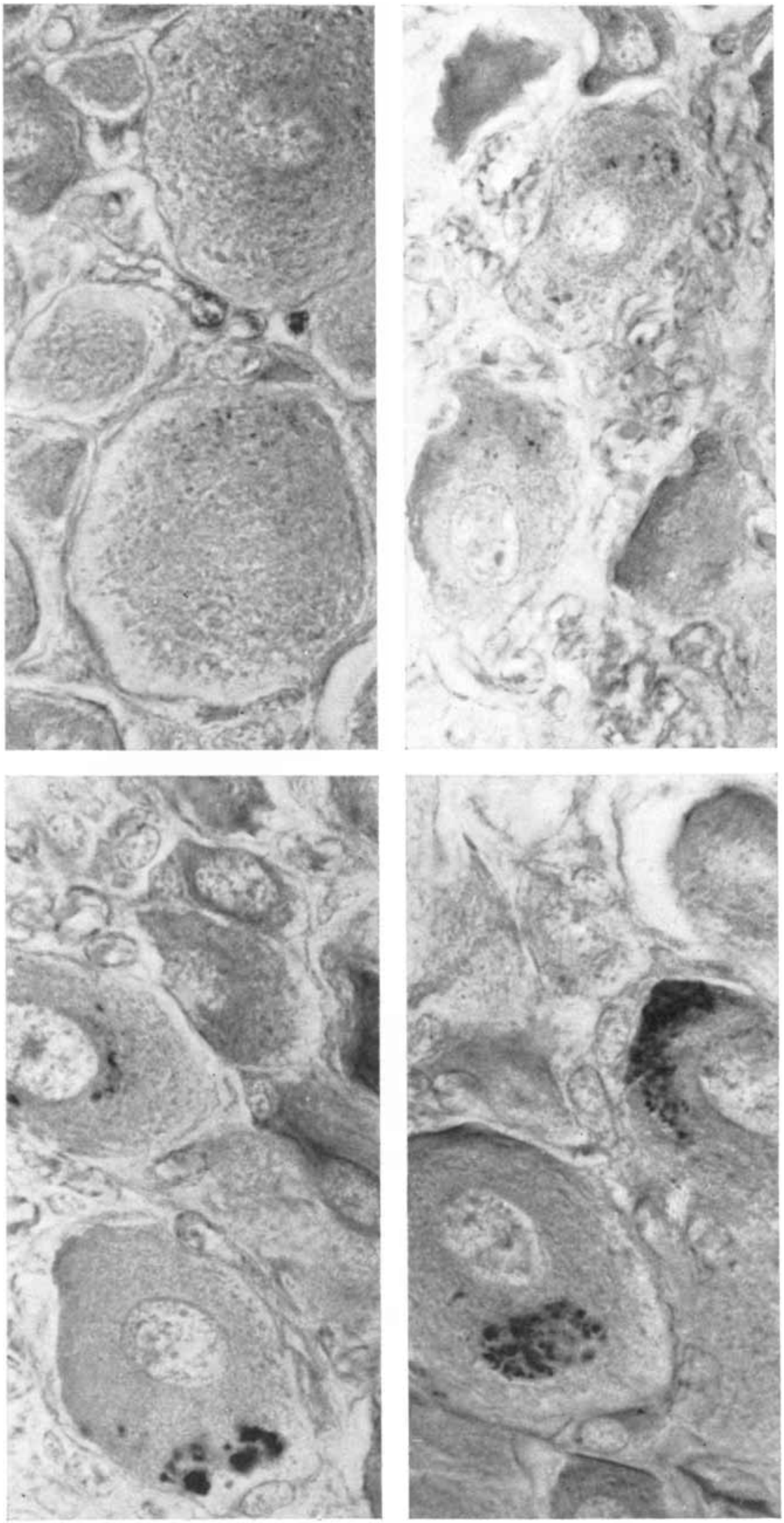
PEROXIDATION OF LIPIDS involves both abstraction and addition. A lipid polymer (*P—H*) first loses a hydrogen atom through abstraction by a peroxide radical, forming a lipid radical (*P•*). Then the lipid adds a molecule of oxygen to form a peroxidized radical (*POO•*), which in turn abstracts a hydrogen, leaving a radical (*P•*) to carry on the chain.

the cell. This hemolysis occurs even when only a small fraction of the lipid in the cell wall is damaged.

A link between lipid peroxidation and aging is found in the chemistry of the age pigments. These materials, a kind of metabolic debris of the cell, are fluorescent brown compounds that accumulate slowly in cells that are not regularly replaced, such as the nondividing cells in the heart, nervous system and lungs. Age pigments are about 60 percent protein, 25 percent lipid and 15 percent carbohydrate. Several observations indicate that radical reactions are probably important in the production of age pigments. The lipid fragments in them appear to be peroxidized, their proteins are cross-linked in ways suggestive of the cross-links found in proteins exposed to peroxidizing lipids and Tappel has shown that lipid peroxidation of some cellular organelles gives materials that have the characteristic fluorescent spectra of the age pigments.

The color-bearing components of these age pigments appear in many cases to belong to the melanin class of compounds, which are also responsible for the color of the pigments of skin, eyes and hair. Melanins consist of large polymeric networks that have been known for more than 15 years to contain free-radical centers that can give rise to ESR signals. Donald C. Borg of Brookhaven has shown recently that some age pigments from various organs produce the type of ESR signals characteristic of melanins, indicating that age pigments also contain free radicals of the melanin type.

Bernard L. Strehler of the University of Southern California and others have shown that age pigments increase almost linearly with age in human heart tissue, for example, and it is clear that these materials are related to aging. Whether they play an important role in the process or are merely harmless byproducts is unknown. The occurrence of peroxidized lipid fragments in these age pigments does prove, however, that lipids are attacked by radicals and are peroxidized in living systems. Furthermore, the fact that lipids are attacked by peroxidizing radicals confirms that reactive free radicals actually are present in living tissue, an assumption that underlies many of the free-radical theories of aging. In this area, as in so many others, it is apparent that the study of radical reactions will continue to provide important new lines of research for chemists and biologists.



AGE PIGMENTS accumulate in cells with age and there is evidence that they are produced in part by radical reactions. Photomicrographs made by Thaddeus Samorajski and his colleagues at the Cleveland Psychiatric Institute compare nerve cells from the dorsal root ganglia of mice four (*top left*), eight (*top right*), 20 (*bottom left*) and 30 (*bottom right*) months old. The increase in size and concentration of the dark granules is clearly seen.

INSECT EGGSHELLS

The scanning electron microscope has revealed that insects' tiny eggs are structurally complex. Their peculiar architecture allows the free exchange of oxygen and carbon dioxide but minimizes the loss of water

by H. E. Hinton

On examining the apparently solid shell of a hen's egg, one may wonder how the egg can absorb the oxygen necessary to sustain the life and development of the embryo inside it. Obviously the shell must be permeable to oxygen; it must therefore have holes that are large enough to allow oxygen molecules to enter. But any holes large enough to allow oxygen molecules to enter will allow water to escape, because water molecules are smaller than oxygen molecules. This difference in the size of oxygen molecules and water molecules need not be hazardous to eggs laid in water or very moist places. But hen's eggs, and the eggs of many insects, are laid in dry places. The differences to be found in the respiratory arrangements of eggs of various kinds are obviously more or less successful attempts made during evolution to resolve the contradictory requirements imposed by dry environments simply because the oxygen molecule is larger than the water molecule.

The smaller an egg is, the greater is the ratio of surface area to volume. The problem of losing water by evaporation through the surface is correspondingly increased. A typical insect egg has about 50 square centimeters of surface area for each milliliter of volume. In a hen's egg this ratio is about 100 times more favorable, and accordingly a hen's egg can tolerate a much higher rate of evaporation. Most insect eggs laid on land have no means of replenishing their water supply. Insects have thus been forced to evolve eggshells that allow the exchange of gases with the air without the loss of too much water.

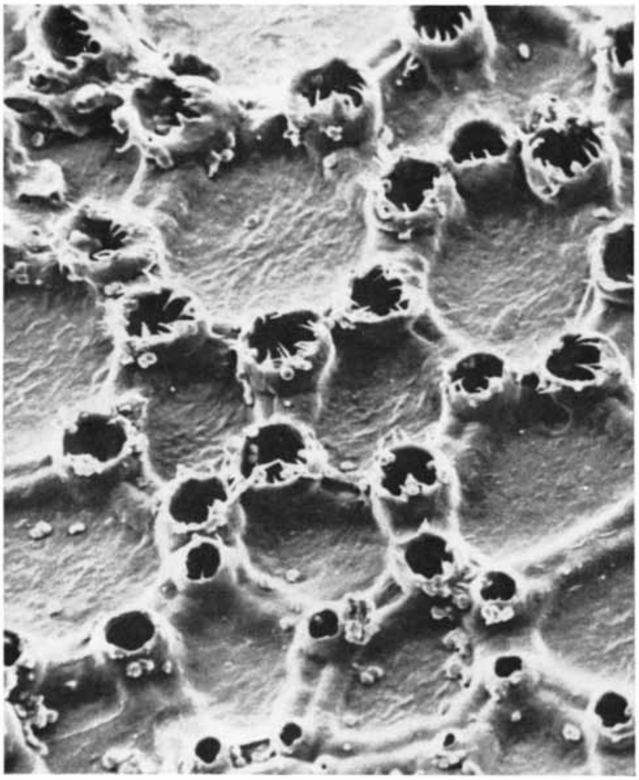
Many investigators have been drawn to the study of this intriguing phenomenon. Over the past decade I have explored the eggshells of a large variety of insects and have found that the shells of terrestrial eggs—those laid on land rather than in water—generally have a remarkably complex structure. The shell is made up of one or more layers of meshwork, each holding a layer of gas. Holes called aeropyles extend through the shell to the outside and connect its gas layers to the ambient air. In some insects (such as grasshoppers, water scorpions and certain beetles) the meshwork spaces fill with gas as the egg dries after it has been laid. In others (such as stick insects and flies) liquid is removed from the meshwork spaces and they are filled with gas while the egg is still immersed in the fluid of the oviduct. Presumably in these eggs liquid from the meshwork spaces must be actively absorbed. This would cause bubbles of gas to form. One can also conjecture that the appearance of gas in the shell may be assisted by the development of a water-repellent coat of fatty material on the struts of the meshwork, which would reduce adhesion between the meshwork and the contained fluid.

The aeropyles that mediate the transfer of gases between the egg and the atmosphere are from about one micron to a few microns wide, and the spaces in the meshwork are about the same width. These dimensions are many times the mean free path of the respiratory gases; the mean free path of oxygen at 23 degrees Celsius is a tenth of a micron. Hence diffusion of the gases and the ambient atmosphere is not significantly impeded. Nevertheless, the structure of the respiratory system of a terrestrial egg is such that comparatively little water is lost to the air as oxygen is taken in.

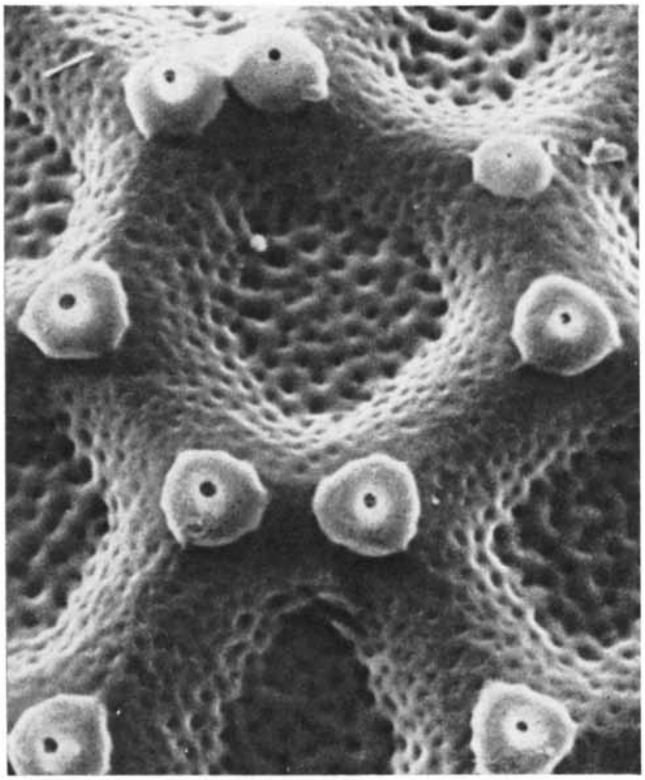
Among those eggs that have one or more layers of gas in the shell two rather different kinds of respiratory system have to be distinguished: those that function as a plastron, or physical gill, when the egg is immersed in water and those that do not. The plastron is simply a gas film of constant volume and an extensive water-air interface. Such a film is held in position by a system of water-repellent structures, and it resists wetting at the hydrostatic pressures to which it is normally subjected in nature. The plastron type of gill makes it possible for an egg to breathe under water indefinitely if there is plenty of oxygen dissolved in the water.

One might ask why a terrestrial egg should have a physical gill that can be used under water. Such eggs are normally glued or fastened in some way to leaves, stones or the earth, and when it rains heavily they necessarily remain submerged in water until it has stopped raining and the water has evaporated or flowed away. Thus in most climates the eggs of terrestrial insects are alternately dry and flooded. To be covered by water for several hours, or even days, a period that may exceed the duration of the egg stage, is no rare and isolated event but a normal hazard of the egg's environment. For this reason one should not be surprised to find that many terrestrial insects and their eggs are adapted for respiration in water quite as well as many aquatic insects. The main difference between the environment in which plastron-equipped aquatic insects flourish and that in which terrestrial insects do is that in the latter environment the flooded periods are shorter and less frequent.

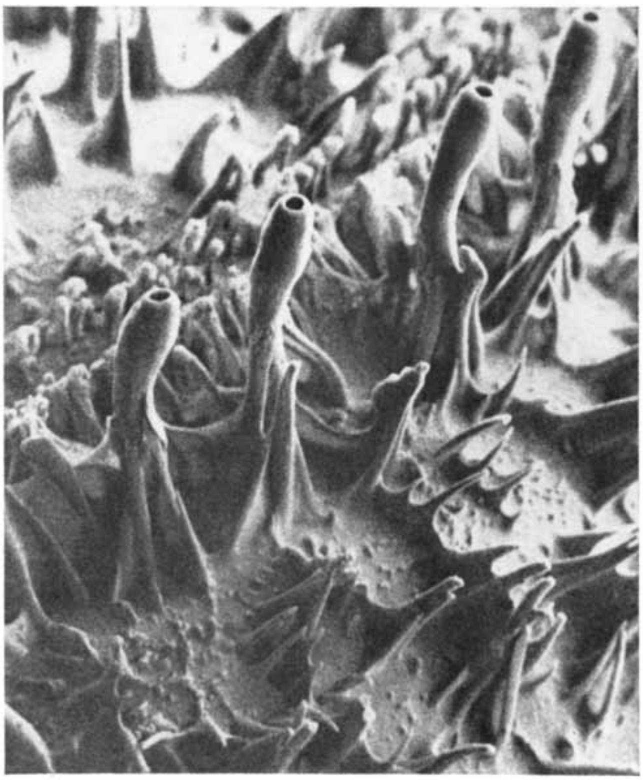
If the respiratory system of the eggshell is to function as a plastron, the total water-air interface across the aeropyles, or across any superficial networks the eggshell may have, must be exten-



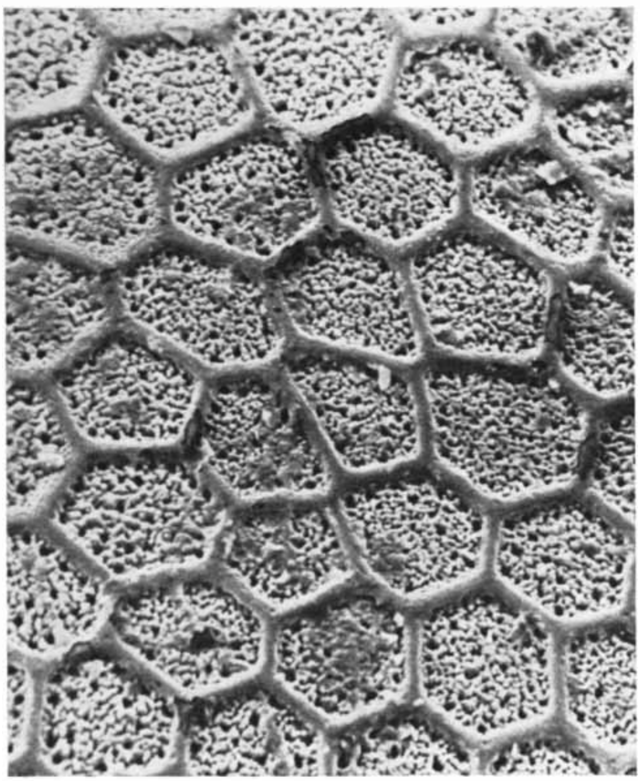
IRREGULAR SURFACE of an insect egg is seen in this scanning electron micrograph; it is the eggshell of the oak silkworm (*Antheraea pernyi*) enlarged 520 times. Ragged holes are outer ends of aeropyles, respiratory tubes leading to the inner layers. Irregularities, along with trapped air, comprise the eggshell's plastron.



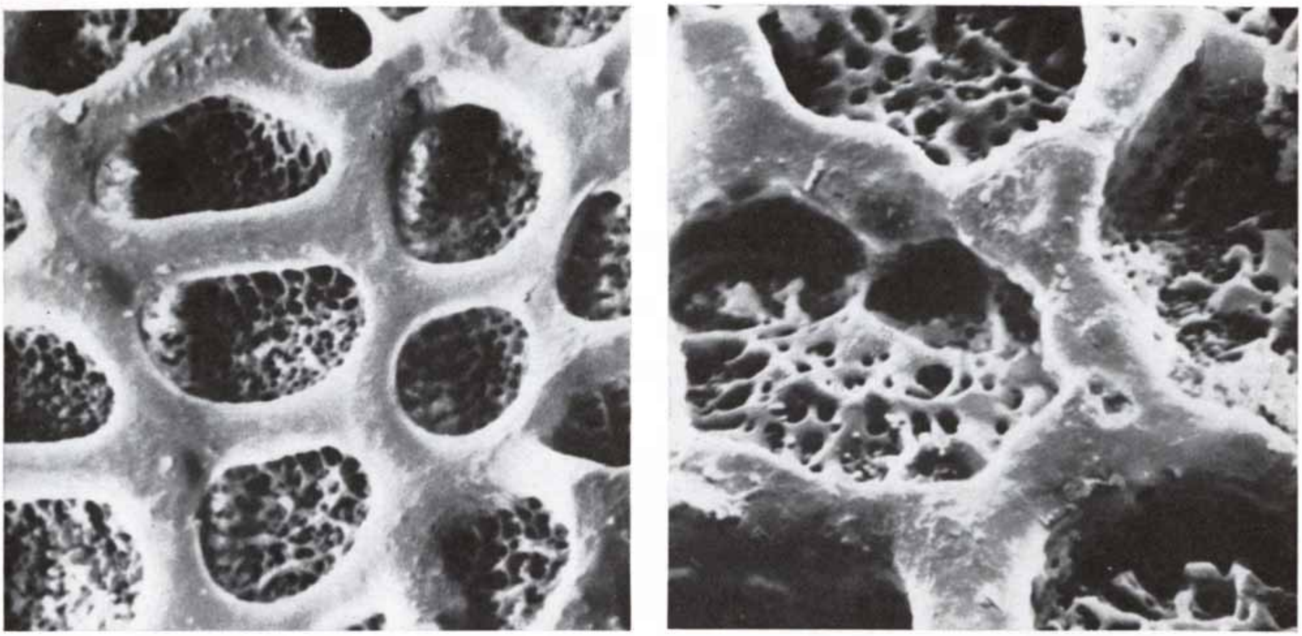
AEROPYLES that jut up from the surface of this moth's egg are seen enlarged 4,300 times; they are much too small and scattered to comprise an efficient plastron. Air trapped by the plastron acts as a gill, allowing underwater respiration. Thus the eggs of this species (*Semiothisa signaria*) could not long survive submerged.



SHELL OF A BUG (*Piezodorus lituratus*) has tall aeropyles that rise from its surface like chimney rows; it is enlarged 340 times.



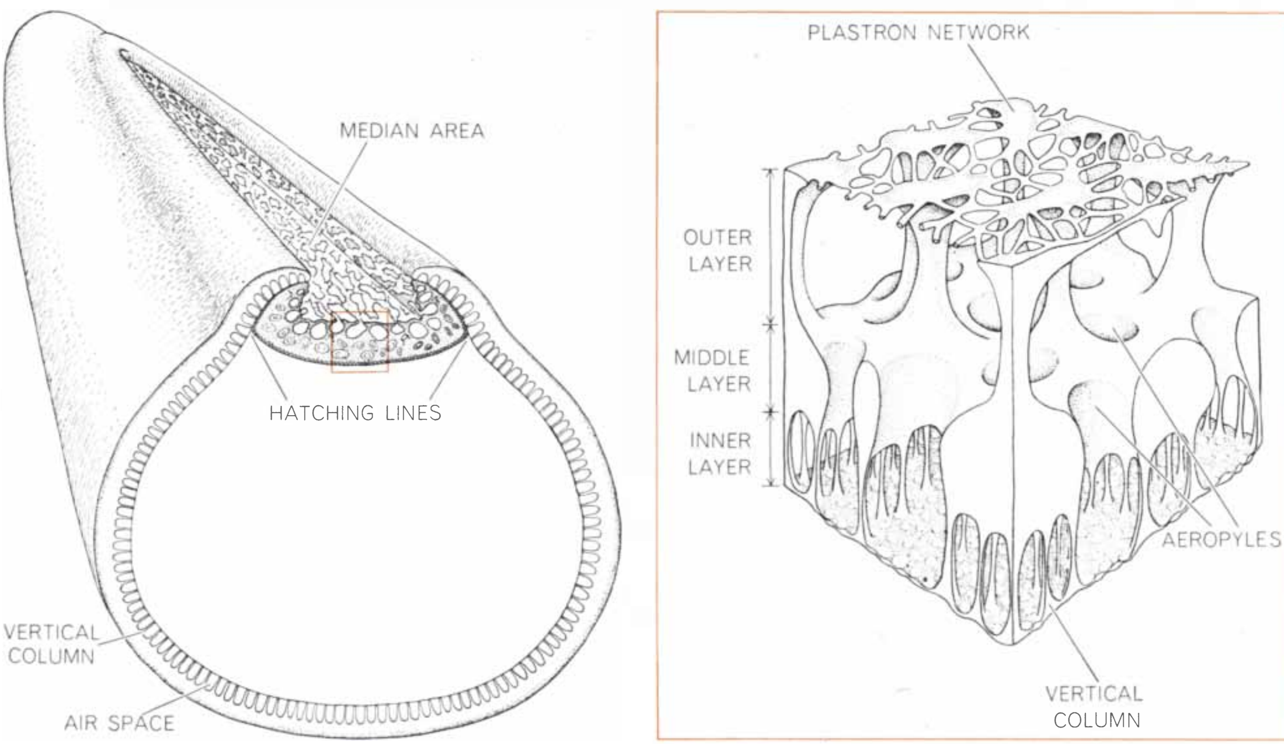
WATER-ADAPTED EGG, that of the giant Indian water bug (*Lethocerus indicus*), is enlarged 820 times to show plastron network.



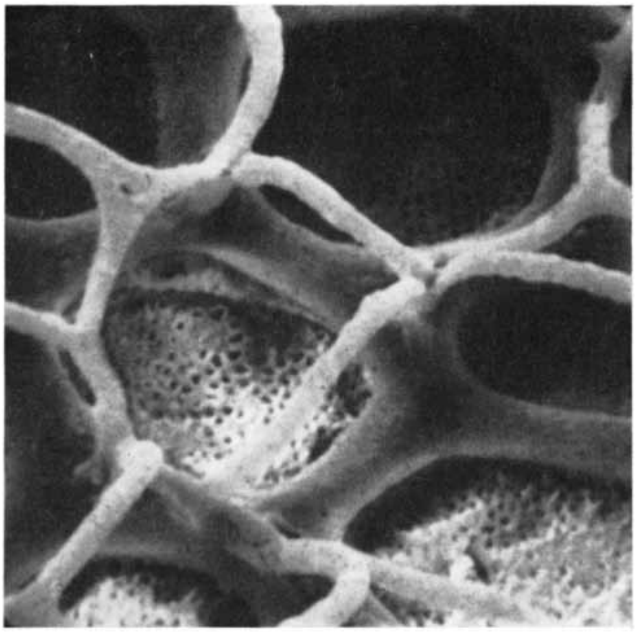
PLASTRON STRUCTURES, possessed by most insect eggs, show considerable variation in structure and location. Four examples are seen in these scanning electron micrographs, prepared during the author's investigation. At far left is an area of the front end of the egg of the long-horned grasshopper (*Plagiostira gilletti*); it is enlarged 2,200 times. Next is an area of the side of the egg of one

sive enough to satisfy a significant part of the oxygen demands of the developing embryo when the egg is in water. When the egg is dry, oxygen is taken in directly through the aeropyles. The plastron thus not only provides a large surface for the extraction of oxygen dissolved in the water but also, when the egg is dry, its network or aeropyles provide a means for the direct entry of oxygen from the air into the shell.

The plastron method of respiration was first discovered in adult aquatic insects, and it was thought that this type of respiration was confined to a few such insects. In 1959, however, I found that the eggs of the fruit fly *Drosophila* and some other terrestrial insects utilized plastron respiration when they were flooded. We now know that plastron respiration is much commoner in terrestrial



ELONGATED EGG of the blowfly (*Calliphora erythrocephala*) is one that confines the plastron structure to a median strip lying between the two hatching lines (*left*). A section of the structure (*color*) is enlarged (*right*) to show the plastron network and the air-filled outer layer underlying it, the meshwork of vertical columns comprising the inner layer, and the aeropyles between.



of the scorpion flies (*Panorpa anomala*); it is seen enlarged 3,000 times. Next is an area on the side of the egg of the fly *Fannia armata*, enlarged 7,500 times; the development of its lacy architecture is shown in the illustrations on page 89. At far right is one of the several plastron "craters" found on the side of the egg of the Australian bush fly (*Musca vetustissima*), enlarged 2,700 times.

insects than it is in aquatic ones. Moreover, it is present not only in the eggs but also in some of the other stages.

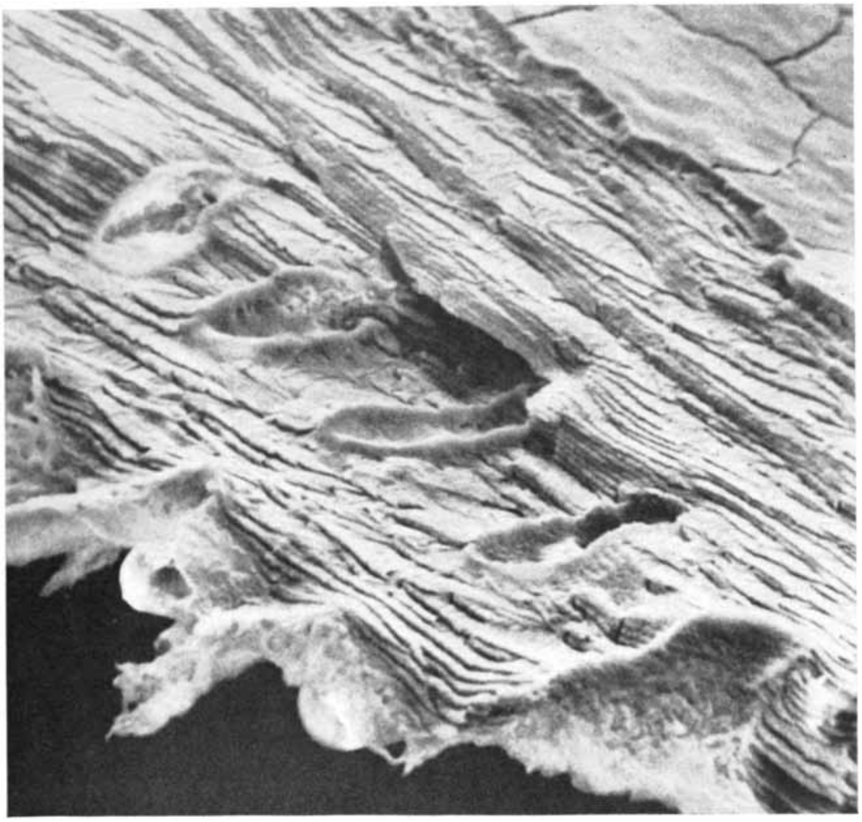
The plastron was evolved in response to two conditions: an environment that was alternately flooded and dry and an environment in which, when it was flooded, the water was rich in oxygen. Obviously if the water's oxygen pressure is lower than the oxygen pressure within the egg, the plastron will work in reverse and will extract oxygen from the egg rather than the ambient water. It is no accident that nearly all the aquatic insects with a plastron are found in waters where the oxygen content is maintained at a fairly high level: rapidly flowing streams, intertidal areas and the littoral of large lakes. The terrestrial insects equipped with plastrons are in much the same boat, so to speak. Their eggs can survive flooding only in oxygen-rich waters, and of course rainwater is rich in oxygen.

For eggs that depend on plastron respiration the problem of preventing loss of water under dry conditions is acute either because they have a great number of aeropyles or because they have an extensive open network. *Drosophila* and many other insects have evolved an answer to this problem in the form of respiratory horns that have a plastron over their surface. If the rest of the egg's surface is impermeable to water, the egg loses water only through the cross-sectional area of the base of the horns, which is only a small part of the entire surface of the horns. When the egg is under water, the entire surface of the horns is available for the extraction of oxygen from the water. It is now known that at least 19 groups of insects have independently evolved respiratory horns with a plastron like that of *Drosophila*.

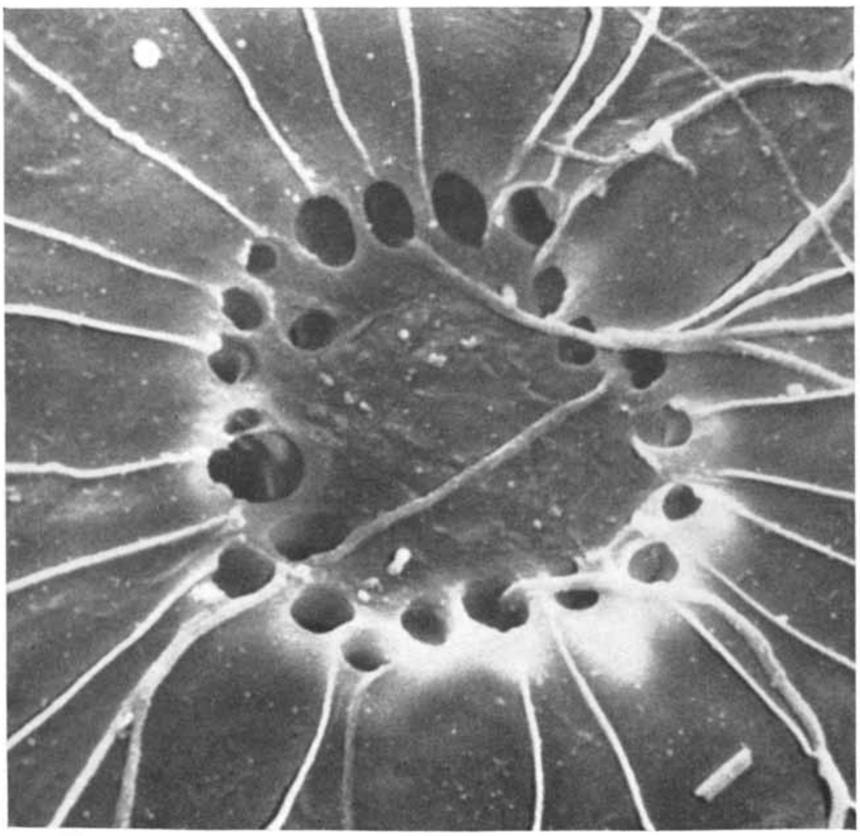
In eggs without respiratory horns the plastron may be an open network over the entire surface (as it is in the egg of the housefly), may be restricted to a certain area or may consist of discrete plastron craters scattered over the surface. In eggs where a large part of the surface is a plastron there is sometimes a membrane under the shell that has only small areas of permeability, so that under dry conditions the respiratory gases are funneled into and out of the egg with a minimum loss of water. When a relatively impermeable membrane is not present under the shell of such an egg, the egg cannot survive being dried. Indeed, many terrestrial eggs that have a plastron over their entire surface are liable to dry up. The egg of the housefly has a plastron over its entire surface but has no impermeable inner membrane; its embryo therefore survives only in terrestrial environments that are very moist.

If a plastron is to serve as an efficient respiratory structure, it must fulfill four requirements: (1) it must resist wetting at the hydrostatic pressures to which it is commonly subjected in water; (2) the geometry of the plastron meshwork and the nature of its surface must be such that it is not wetted when the surface tension of the water is lowered by surface-active substances; (3) its total area must be large enough to satisfy the egg's need for oxygen, and (4) the drop in oxygen pressure along the length of the plastron should be small so that all the plastron can be effectively used. W. H. Thorpe and D. J. Crisp of the University of Cambridge established these criteria many years ago in their studies of adult aquatic insects. I have found that the same criteria apply to the plastrons of terrestrial insect eggs.

The first thing I had to find out about the resistance of egg plastrons to hydrostatic pressure was whether or not they could withstand the impact of falling raindrops. After all, many eggs are laid in places such as the surface of a leaf, where they are not protected from being hit by raindrops. One can calculate that the pressure a raindrop exerts in falling on a plastron is equivalent to a head of water about 1,000 times the diameter of the drop. Thus a large raindrop four millimeters in diameter would strike the plastron with a pressure amounting to about 31 centimeters of mercury. My observations in the field showed that eggs with plastrons were not wetted by raindrops. The reason was that a raindrop falling on the plastron exerts its high pressure for only about a millisecond; I found by experiment that even the plastrons least resistant to wetting



MULTIPLE LAYERS comprising the eggshell of the puss moth (*Cerura vinula*) are visible in this scanning electron micrograph. Broken edge of shell is seen enlarged 1,950 times.



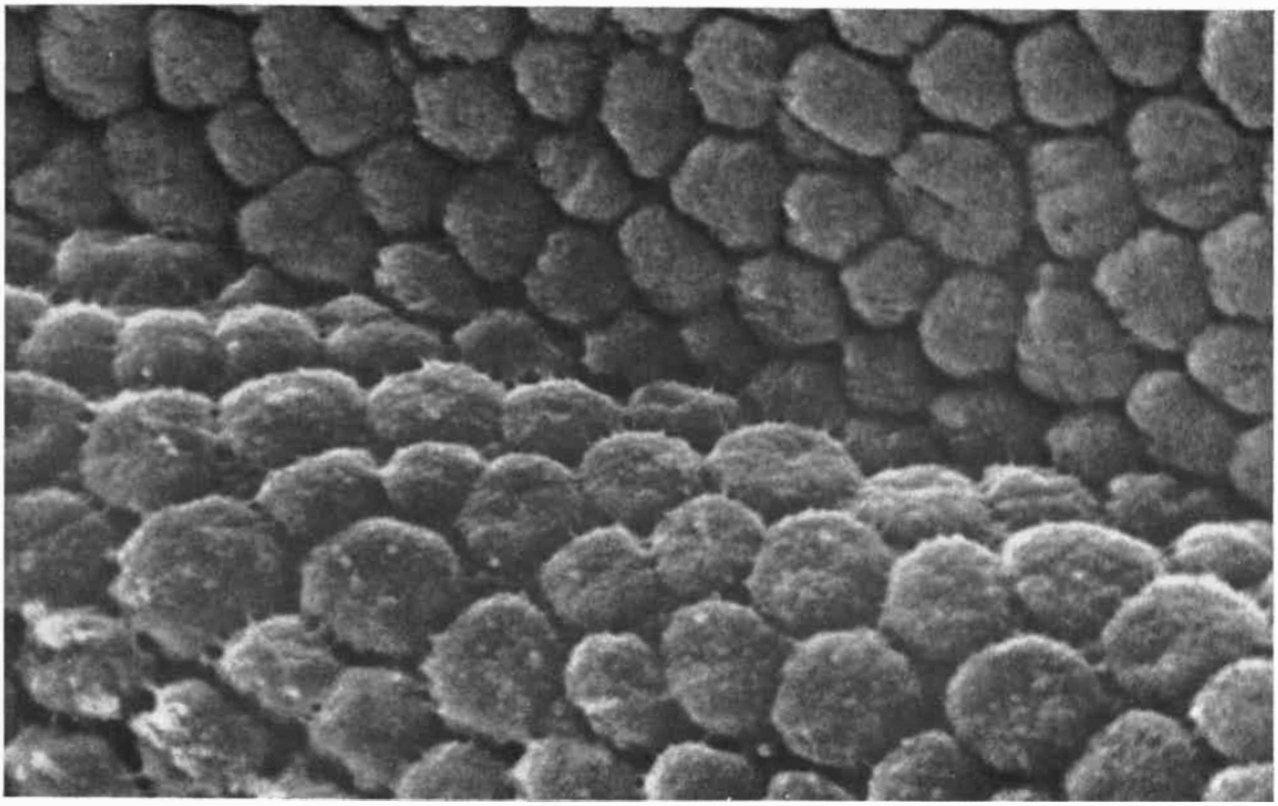
SMALL TUNNELS, or micropyles, in eggshells provide a way for the fertilizing sperm to reach the interior of the egg. These are micropyles in a puss-moth egg, enlarged 4,600 times.

could withstand such pressures for about 30 minutes.

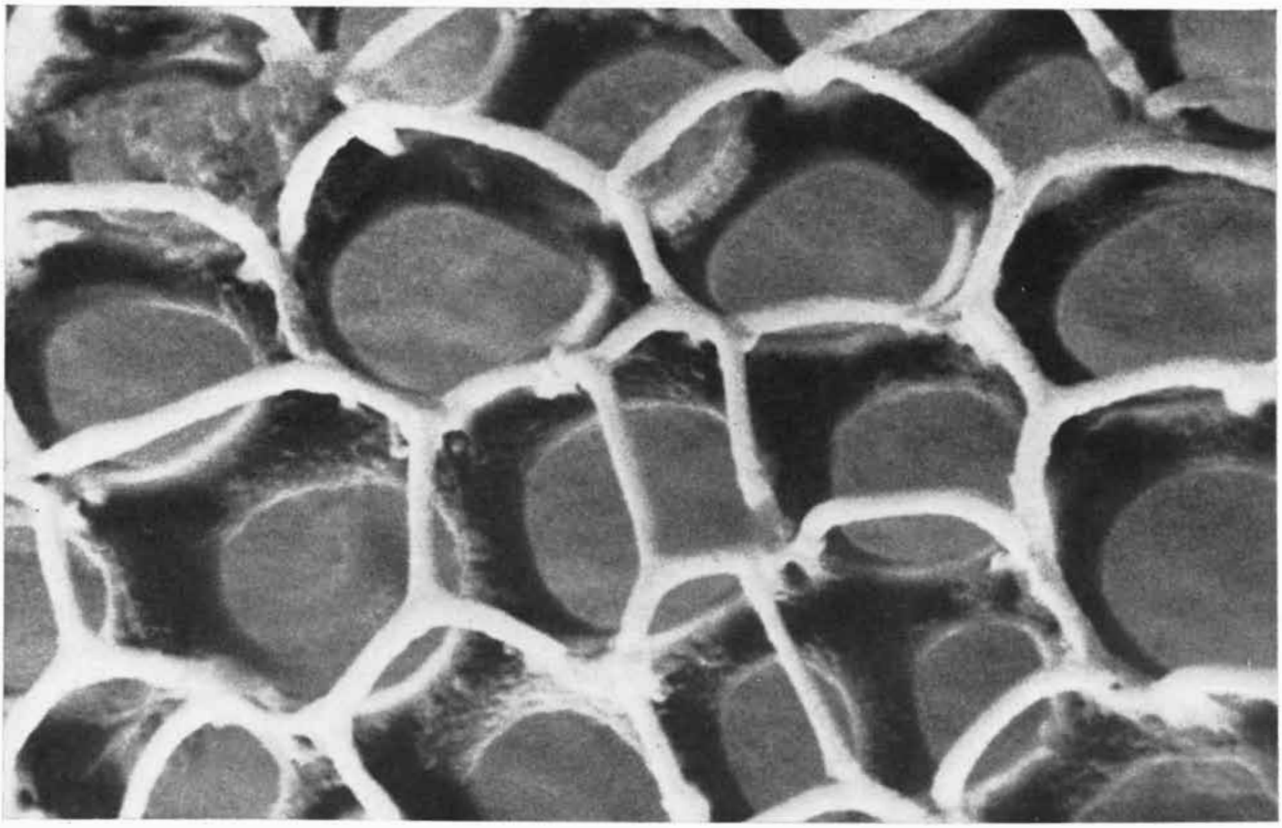
Even in a heavy rainfall terrestrial eggs are not usually exposed to hydrostatic pressures such as insects living in streams have to tolerate. It was therefore a surprise to find that the plastrons of terrestrial eggs often showed a greater resistance to wetting by hydrostatic pressures than the plastron of the typical aquatic insect. For instance, the plastron of the terrestrial egg of *Drosophila funebris* was found to resist a pressure of 1.3 atmospheres above normal atmospheric pressure, whereas the plastron of the aquatic pupa of the fly *Antocha vitripennis* could resist only an excess pressure of a third of an atmosphere.

An explanation of this seeming paradox emerged when I looked into the effects of surface-active substances on the resistance of plastrons to wetting. In the clean waters of the streams where aquatic plastron-bearing insects live the surface tension of the water is high, usually between 70 and 72 dynes per centimeter. In contrast, terrestrial eggs, which are commonly laid on organic matter, are exposed to high concentrations of surface-active substances in the puddles of rainwater deposited on such matter. Surface-active substances lower the surface tension of the water, so that it more readily wets the plastron; the resistance of a plastron to wetting by excess pressures varies directly with the surface tension of the water. In response the plastron of many terrestrial eggs has undergone evolutionary changes in its geometry or in the nature of the surface of the meshwork struts that increase its resistance to wetting by surface-active substances. Such changes automatically increase the plastron's resistance to wetting by excess hydrostatic pressures in clean water. The consequence of such changes is that the resistance of the plastron of many terrestrial eggs to high pressures is appreciably greater than the resistance of the plastron of many aquatic insects.

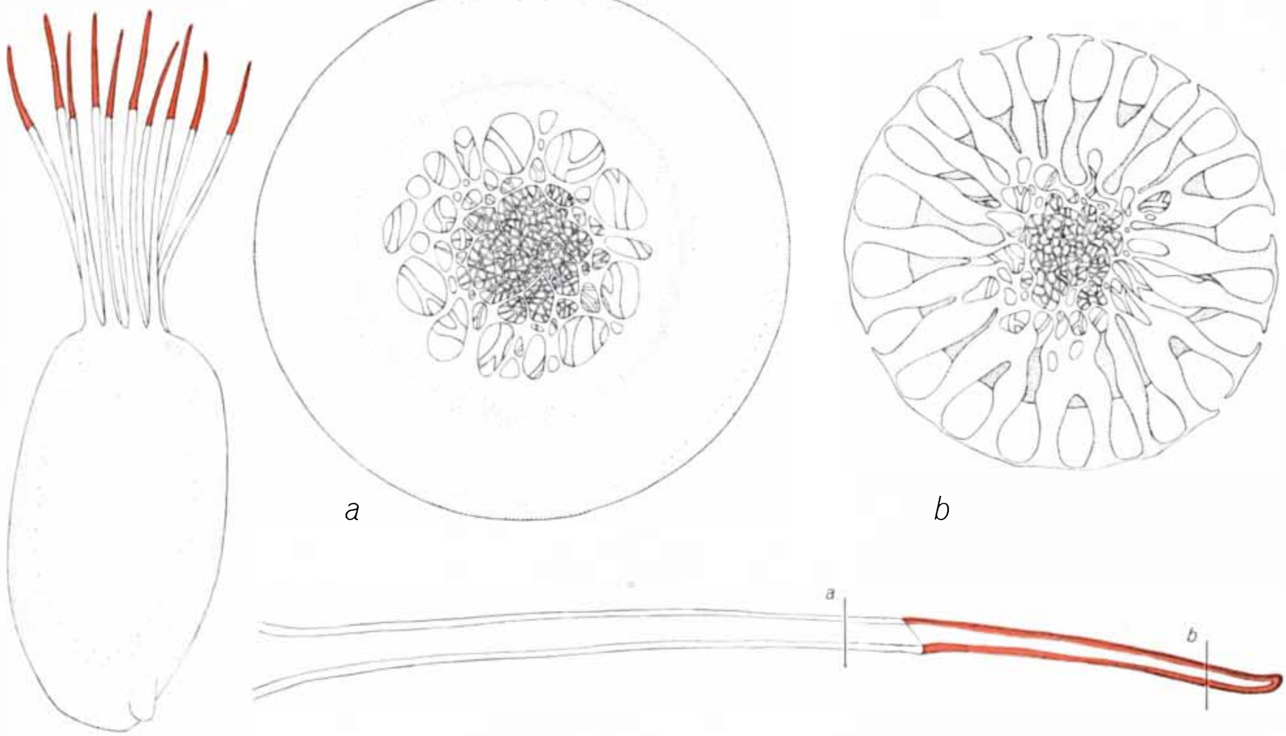
Most of the terrestrial plastrons I tested were those of species that lay their eggs in cow dung or in decomposing vegetable or animal matter. These eggs could be placed in two distinct groups according to the resistance of their plastron to excess hydrostatic pressure. The first group included only those eggs found in cow dung. The plastron of these eggs was able to withstand excess pressures of up to 30 centimeters of mercury for about 30 minutes or more, but its resistance fell off rapidly at higher



SURFACE CELLS of the ovarian follicles in the fly *Fannia armata* are enlarged 1,500 times in this scanning electron micrograph. These are the cells that secrete the eggshell; their distribution determines the pattern of the egg surface (*see illustration below*).

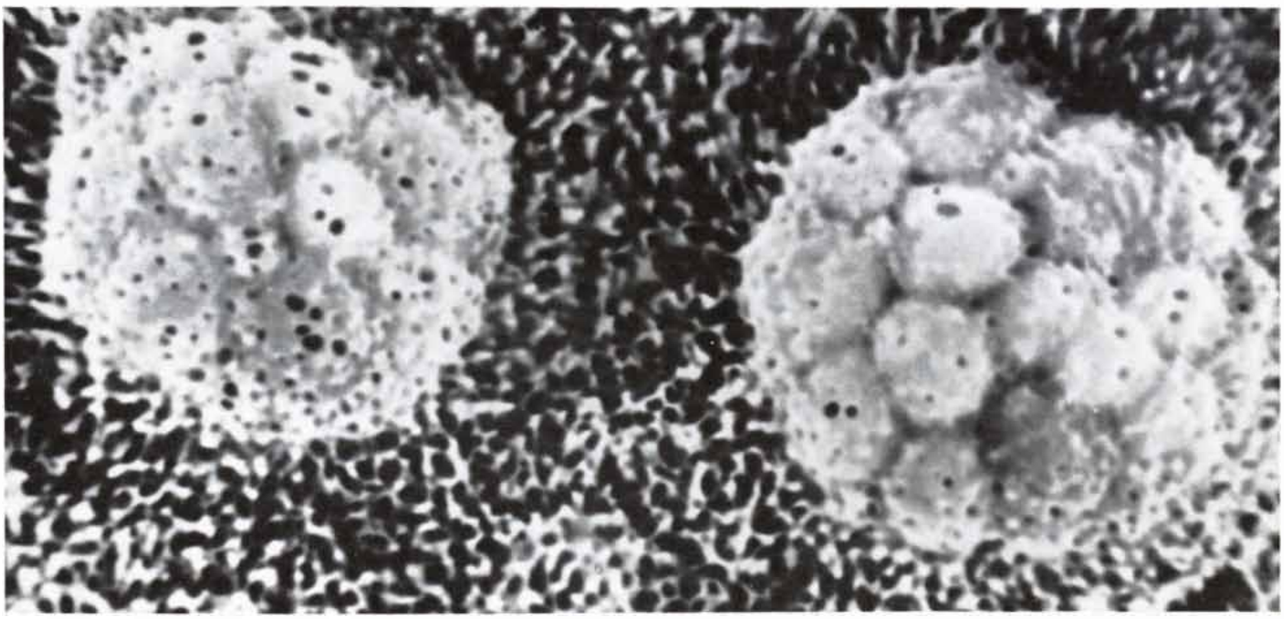


INCOMPLETE EGG, removed from the ovary of a fly of the same species, is seen enlarged 4,800 times. In most places the lacy net of shell surface remains in contact with the follicular cells. The completed shell will look like the one at top left on page 87.



HORNED EGG of the European water scorpion (*Nepa rubra*) has its plastron structures confined to the tips of the horns (*left, color*). Water loss during respiration is minimized because the impervious surface (*a*) is much greater in extent than the plastron area (*b*).

pressures. In the second group, represented by *Drosophila* and the blowflies, the plastron withstood considerably higher excess pressures (in the range of from 60 to 100 centimeters of mercury) for 30 minutes or more. This difference is of particular interest because when the surface tension of the rainwater puddles on cow dung was compared with the surface tension of water standing on decomposing flesh, it was found that the former was consistently higher (50 dynes per centimeter compared with 39 or 40 dynes per centimeter for water standing on flesh). The difference between the surface tension of water on cow dung and that of water on decomposing flesh or vegetable matter is understandable; liquefying flesh or vegetable matter, still containing most of its fats and proteins, would be expected to produce higher concentrations of organic acids and other surface-active substances than cow dung, which consists mainly of lignin



INTERNAL APPEARANCE of a plastron structure is revealed by a scanning electron micrograph. The surface of an egg of the stone fly (*Pteronarcys dorsata*) is seen on the left-hand page. Shown is a part of the plastron area, enlarged 2,700 times. The same area is and cellulose and decomposes slowly.

Many terrestrial eggs of butterflies and other insects do not have a plastron but nevertheless have a layer of gas in the inner part of the eggshell. Aeropyles extend from the gas film to the outer surface of the shell; it is through these aeropyles that gas is exchanged with the ambient air. Such eggs are distinguished from plastron eggs only because the number of their aeropyles is so small that when the egg is under water, the total water-air interface established across the outer openings of the aeropyles is not large enough to extract the amount of oxygen from the surrounding water necessary for the development of the embryo.

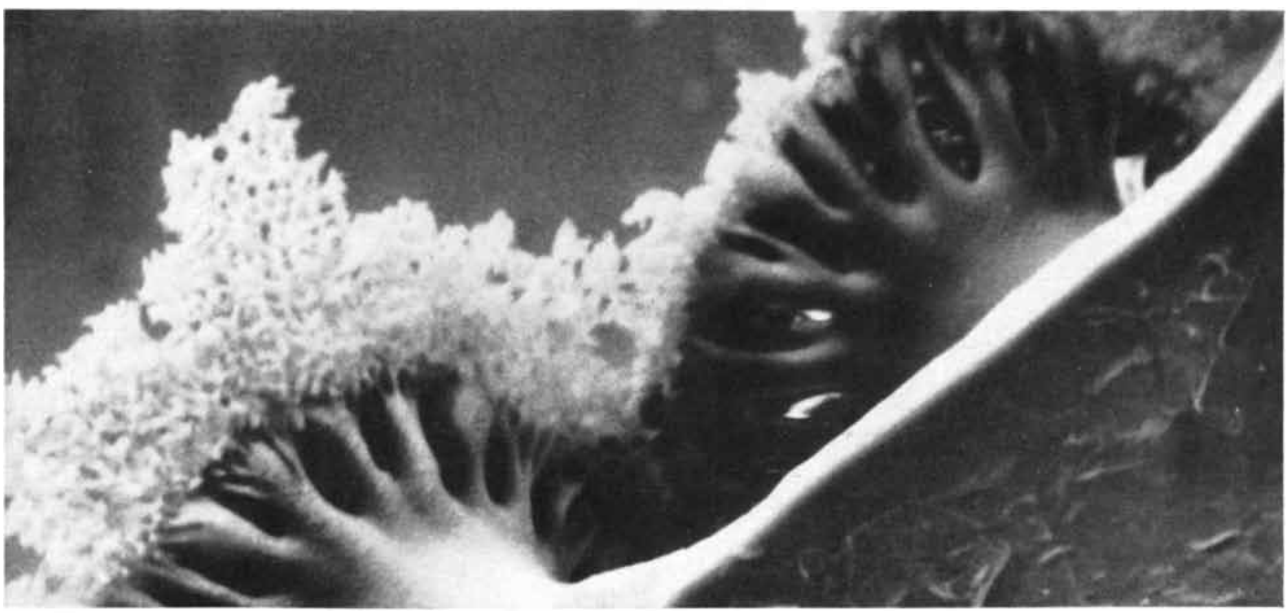
In eggs that do not have a plastron the aeropyles may be scattered evenly over the egg's surface or arrayed in bands, as they are in the eggs of some moths and beetles, or they may be clustered at the front end of the egg, as they are in the eggs of many bugs. In the eggs of some butterflies and other insects the aeropyles open on the crest of longitudinal ridges. The eggs of tortoiseshell butterflies and of some other insects have a particularly interesting defense against drowning, although they lack a plastron. These eggs are laid in masses. When it rains, a bubble of air is sometimes trapped over the front end of the mass. The bubble cannot resist pressure but, in the absence of a pressure difference that would collapse it, it functions as a temporary gill extracting oxygen from the surrounding water. The eggs extract much more oxygen from the bubble than it originally contained. As oxygen is withdrawn from the bubble, equilibrium tends to be restored by oxygen entering rather than by nitrogen leaving; nitrogen is much less soluble than oxygen and so passes through the air-water interface of the bubble much more slowly. Nevertheless, a little nitrogen is continually escaping and in time the bubble becomes too small to be effective as a gill.

Many terrestrial eggs, even some of those without a plastron, have their aeropyle openings on stalks that, like a diver's snorkel, give the egg access to the air. Thus the stalks can take in atmospheric oxygen while the rest of the egg is covered with water. In the eggs of some bugs these stalks are very long indeed, sometimes more than half as long as the egg itself. The stalk often serves not only to bring in air but also to deliver sperm to the egg by way of a special channel in the center of the stalk.

Many insects lay their eggs in water, but we would not expect to find elaborate respiratory systems in eggs that do not have the problem of losing water when breathing. In fact, I have not been able to find such systems in the eggshells of mayflies, caddis flies or most of the primitive two-winged flies. The eggs of these species have no layer of gas in the shell or any other distinct apparatus for respiration. Apparently they use the entire shell for this purpose, simply taking up dissolved oxygen from the water that bathes them. When the shell is examined with a light microscope or a low-resolution electron microscope, it appears to be solid. At high resolutions, however, the shell is seen to be composed of a meshwork of fibrils about 10 to 15 angstroms in diameter. The spaces between the fibrils are about 20 angstroms wide, quite wide enough to allow the diffusion of gases through the shell.

Some eggs are laid in shallow streams and other bodies of water that are liable to dry up, and among such eggs we might well expect to find the same kinds of elaborate respiratory system as those of terrestrial eggs. Indeed, the eggs of stone flies, of some bugs such as water scorpions and of many of the advanced two-winged flies have a highly developed plastron by means of which they extract oxygen from the water. Their elaborate respiratory structures also safeguard them against losing too much water while breathing when they are left high and dry, a hazard they often experience.

Some insects such as midges and caddis flies that lay their eggs in aquatic habitats that may dry up fairly suddenly embed their eggs in a hygroscopic jelly produced by the female. The jelly not only serves as a protection against small predators but also can tide the eggs over a short period of dryness, since the jelly gives up water slowly. It is intriguing that many midges and a few caddis flies also lay their eggs in a mass of jelly on leaves and other objects on land. The shell structure of these eggs resembles that of eggs laid under water, and they are in effect in a liquid or semiliquid medium even though they are terrestrial.



seen after tearing on the right-hand page; it is enlarged 2,800 times. The view is oblique, from the interior outward. Two of the many treelike structures that comprise the plastron are visible; the finely ramified tops intermesh to form the egg's water-air interface.

Medieval Uses of Air

Technology came before science in the invention of the blast furnace, the windmill and the suction pump. Medieval workers also constructed a manned glider and a useful gas turbine and conceived the parachute

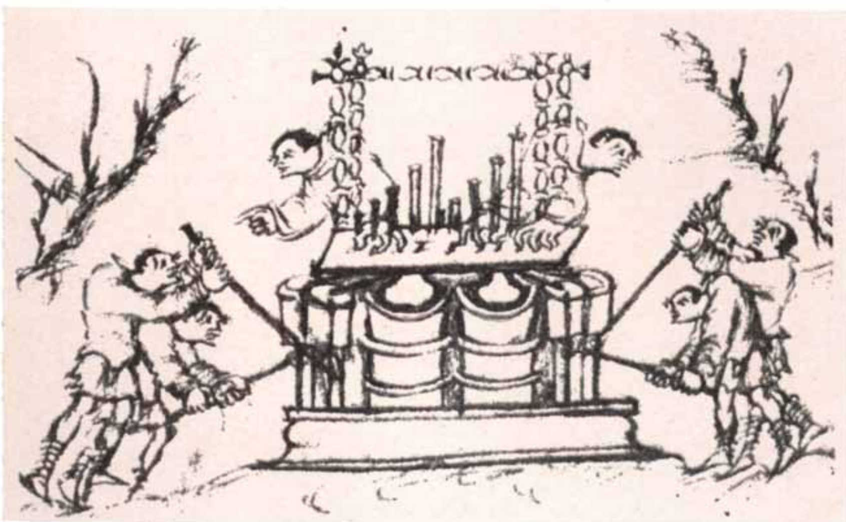
by Lynn White, Jr.

Most of us who live in the latter decades of the 20th century take it for granted that advances in technology represent practical applications of earlier scientific discoveries. In our vernacular the term "science and technology" is subconsciously hyphenated; once when I tried to refer in print to technology and science the typesetter "corrected" the sequence. In actuality the marriage of technology and science is not more than a century and a quarter old. Architects since antiquity have used mathematics to achieve aesthetic effects, but mathematics played no significant part in their engineering. Although astronomers, from the 15th century on, worked at improving the art of navigation, the vast majority of sea captains, even on great oceanic voyages, long preferred to rely on their own empirical methods of getting where they wanted to go. During the 18th century chemical science began to stimulate industrial chemistry, particularly in France, but it was not until the middle of the 19th century that our present assumption—that a better way of doing something is almost always based on a new scientific discovery—became widespread.

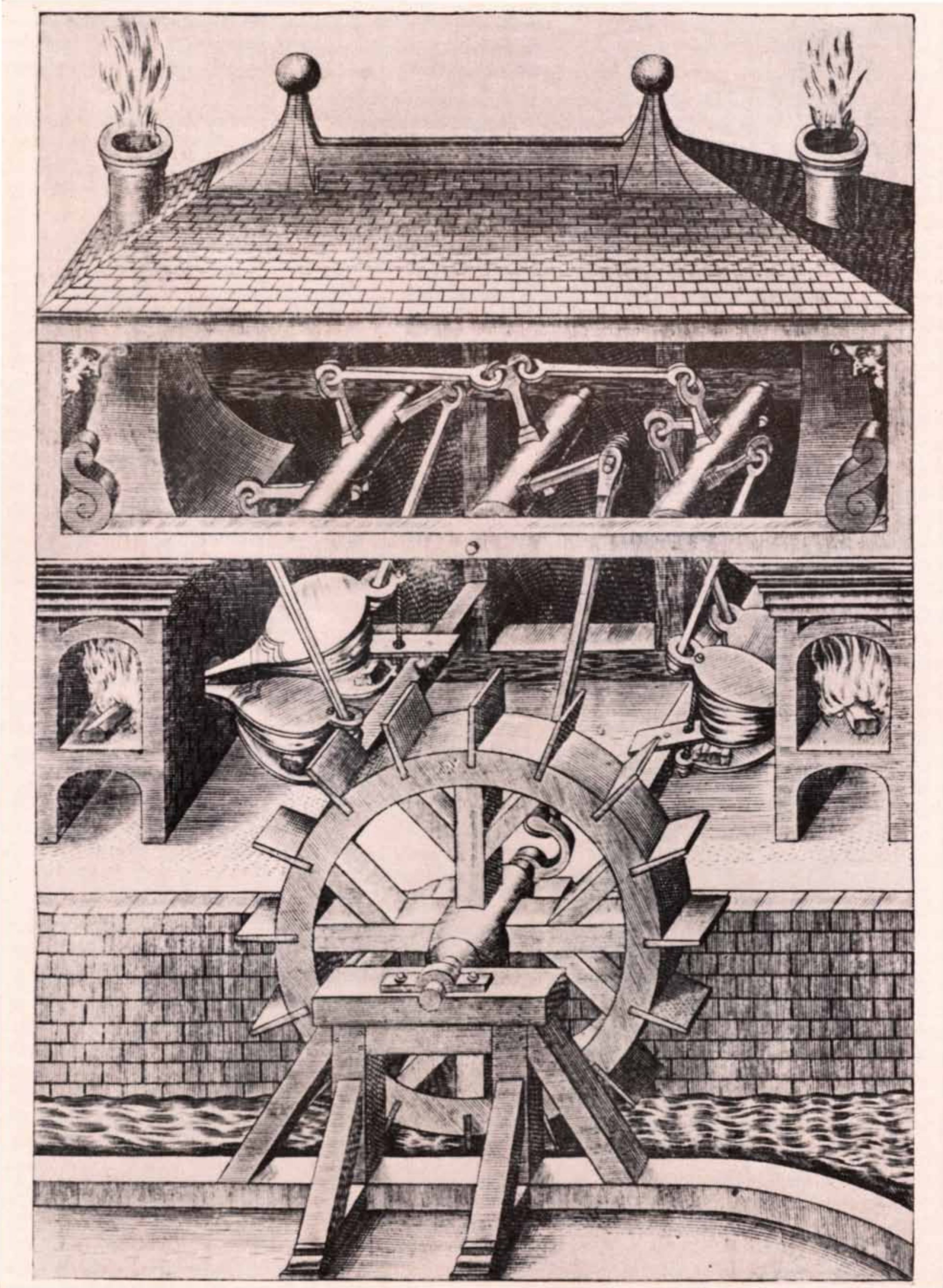
Before that time science and technology lived apart. Science had been a largely speculative effort to understand nature, whereas technology was an exclusively practical attempt to use nature for human purposes. The two seldom interacted; Francis Bacon had said that "knowledge is power," but he did nothing to validate his dictum and not many were listening. It was only in the decades of the younger Queen Victoria, Napoleon III and Bismarck that this idea became normal in Europe. Its general recognition in America took a bit longer (even though when Benjamin Franklin founded the American Philosophical Society in the middle of the preceding century, its purpose was specified as "the promotion of *useful* knowledge").

How did technicians operate before they learned to get innovative ideas from science—indeed, before science had reached a state that could provide many such ideas? The Greek and Arabic mathematics and physics that western Europe absorbed almost completely when they appeared in new Latin translations during the 12th and 13th centuries were not of the slightest assistance to the engineers of that age. Yet the same engineers, with unprecedented daring and ingenuity, raised the vast Gothic cathedrals that still grip us by the throat when we see them. We underestimate today what keen empirical perception can produce by way of technological novelty quite unrelated to scientific thinking.

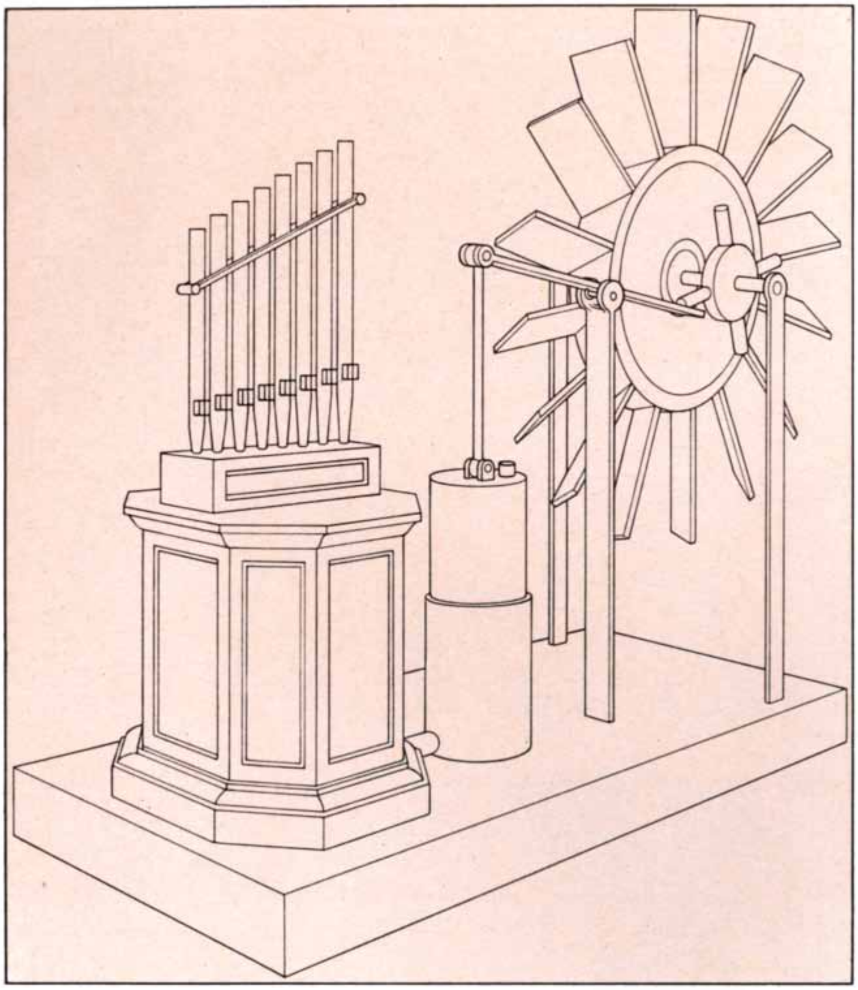
In retrospect basic inventions often seem incredibly simple. The long delays between their appearance in the course of human history, however, make one wonder what we mean by "simple." The Greeks and Romans were sophisticated in many ways: in drama, law, sculpture, philosophy, geometry and much else. But no Greek or Roman ever saw the common, twice-bent lever we call a crank. To be sure, the Chinese who were contemporary with imperial Rome knew about cranks, but this most ordinary means of connecting reciprocating motion with continuous rotary motion, which in machine design is second in importance only to the wheel, does not show itself in the West until it is pictured in the Utrecht Psalter, a work produced near Reims between A.D. 816 and 834. Did it diffuse from China? A crank



MEDIEVAL PIPE ORGAN, with a crew of four busy at the bellows, is shown in one of the illuminations of the Utrecht Psalter, a work produced between A.D. 816 and 834. Larger and larger bellows, worked by water power rather than manpower (*see illustration on opposite page*), led eventually to the first European blast furnaces and the casting of iron.



TWO PAIRS OF BELLOWS, driven by crankshaft and connecting rod attached to a waterwheel, provide the air current needed to keep up high furnace temperatures in a 16th-century smithy. The plate is in *Le diverse et artificiose machine,* published in 1588.



WINDMILL with a horizontal axle bearing cogs was proposed by the mechanical genius of the first century after Christ, Hero of Alexandria, to raise the piston of the gravity-powered air pump for a pipe organ. Hero's suggestion for a new source of power was evidently ignored and the windmill was independently reinvented twice in the following centuries.

is scarcely borrowable apart from some more complex apparatus; the picture in the Utrecht Psalter shows it turning the first rotary grindstone known anywhere. The second use of the crank in Europe was with the hurdy-gurdy in the 10th century. Since neither rotary grindstones nor hurdy-gurdies were known in China, it would seem that the crank was invented independently by two artisans widely separated in time and space: first by a Chinese of the Han Dynasty and then by a Frank under the Carolingians. To bend a lever twice is indeed "simple." To see that something new and useful can be done with this distortion demands empirical genius. Elaboration of something already known, it appears, is a far easier achievement than a genuine new insight, however simple. It is my purpose here to examine a few insights that occurred during the later medieval period.

Outside the laboratory we experience the physical world in terms of somewhat naïve categories. The ancients named four: earth, air, fire and water. Of these air is the most puzzling in our normal contacts with it because, although we are enveloped by it, we neither see nor grasp it. Yet air can be exploited for technological purposes, and in medieval times a number of empirical efforts were made to put air to work. All these efforts were simple. Some were of great immediate importance and others were of great seminal significance in the growth of Western culture.

Of course, scientists as well as artisans were interested in air in the Middle Ages. Indeed, the greatest controversy in medieval physics—the challenge of Aristotle's theory of motion—had much to say about air. Aristotle believed a moving object could continue in motion only as long as something moved it. In the case of a projectile, air displaced by compression in front of the object came around behind it and pushed it along. The new medieval theory of "impetus" insisted that a moving object continues to move until it is stopped by resistance: air has nothing to do with motion except insofar as it is a cause of friction. The anti-Aristotelian scientists of the 14th century used the rotary grindstone (a device that, as we have seen, was unknown to Aristotle) as a favorite nonspeculative proof of their position. The grindstone still turned for a time after the grinder's hand left the crank, but its motion, unlike the motion of a traveling projectile, displaced no air. Therefore the grindstone moved not by pressure of air but by impetus until the resistance of friction at the axle stopped it. The new physics of Jean Buridan and others laid the foundations for the work of Galileo and Newton. Still, we have no indication that at the time there was any relation between the science of air and the technology of air.

Since at least Neolithic times men have made moving air do work by using sails to capture the force of the wind and propel boats. In the first century B.C. the fore-and-aft rig appeared in the Mediterranean, enabling small boats to run into the wind at a fairly sharp angle. Big merchant ships were not equipped with triangular lateen sails, however, until the sixth century. The delay was probably due to the slow development of keels that bit deep into the water and thus reduced the sideways drift involved in tacking. Because keels are not discussed in any contemporary document, and because all pictures extant show ships afloat with the keel hidden, how the deep keel actually evolved is a question that must be left to underwater archaeologists. In any case, mariners continued to experiment with sails and rigging throughout the Middle Ages, adding masts and subdividing sails to achieve greater power and flexibility of control. Their cumulative successes by the end of the 15th century were an element in making possible the great voyages of Columbus and Vasco da Gama.

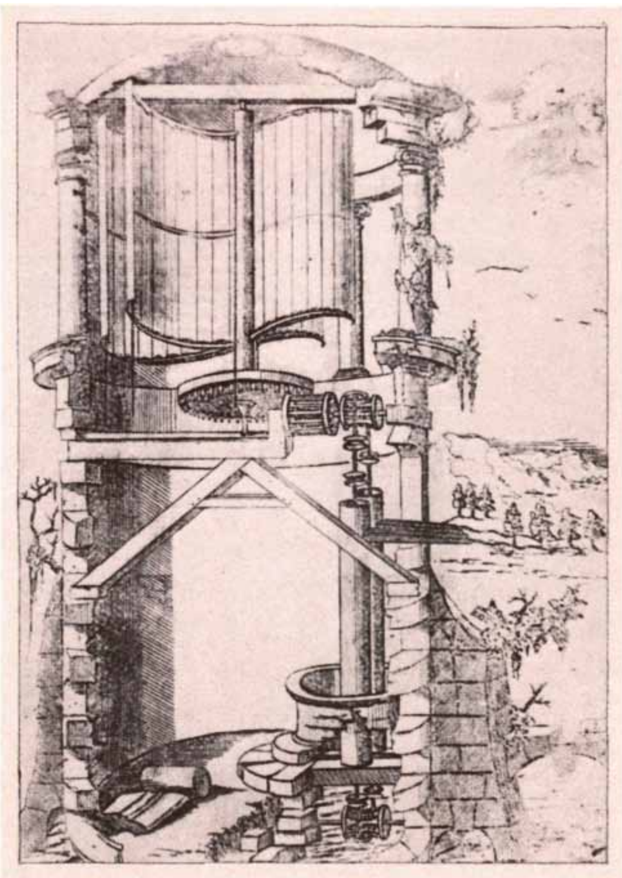
How to use compressed air in pipe organs was a discovery of the Hellenistic age. The "boxes of whistles" were costly, and their machinery was so complicated that maintenance was difficult. Indeed, the pipe organ is the most intricate apparatus known before the invention of mechanical clocks in the 14th century. It is therefore not surprising that organs vanished from the West after the barbarian invasions. The Byzantine world, however, enjoyed perfect continuity with the Roman Empire, and organs continued to be used there for secular ceremonies and celebrations, notably in the imperial palace at Constantinople.

In A.D. 757 the Greek Emperor sent a pipe organ as a gift to Pepin the Short, King of the Franks. Pepin used it not in his chapel but in his palace; its fate is unknown. In 826 the Western Emperor, Louis the Pious, commissioned a Venetian priest named George, who had doubtless learned the art of building organs in Constantinople, to construct one for his palace at Aachen in the Rhineland. George's construction may well have looked like an organ shown in the Utrecht Psalter; clearly the Benedictine monk who illuminated that manuscript was interested in machines.

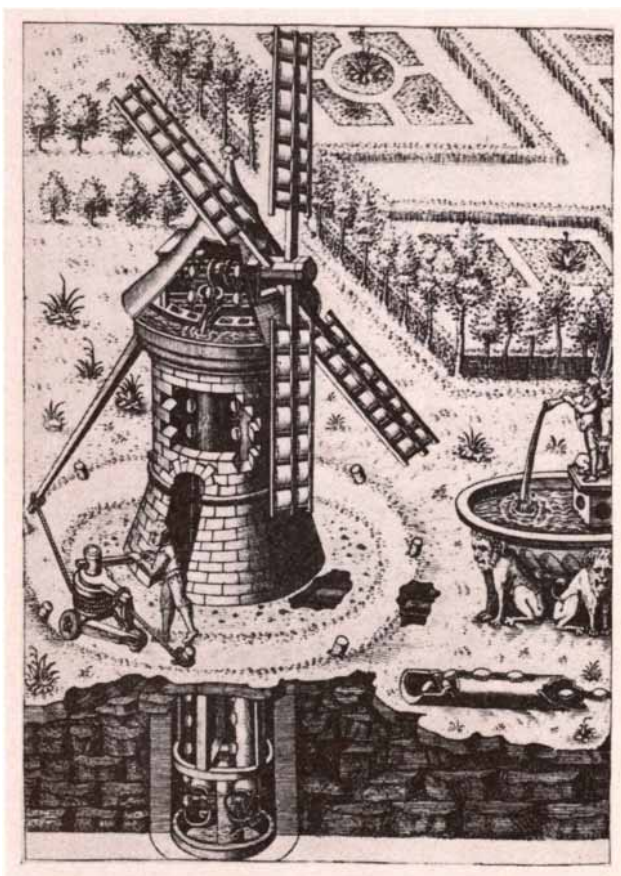
George later became an abbot, and organs began to appear in Western monasteries. Toward the end of the 10th century Elfeg, bishop of Winchester, installed the first monster organ known to us in his cathedral there. It took 70 men pumping 26 bellows to supply wind for the Winchester organ's 400 pipes. The Greeks never allowed organs in their churches: mechanized music was considered alien to religion. The Latin church, however, took the box of whistles to its bosom and made it the typical instrument of Western religious music. With the later invention of the mechanical clock the same contrast of attitudes showed itself again. Clocks proliferated as exterior and interior displays in Western churches, but the Eastern church banned them from its shrines on the ground that eternity must not be contaminated by time's measurement. Until recently the West has felt no such antagonism between mechanization and spirituality.

The organs that reappeared in the West were kept in repair by local craftsmen. Working with the big bellows of these machines would have given such men ideas. It is no accident that at about the time of the building of the Winchester organ we find the first evidence for the use of water power at a smithy. The first documents do not tell us whether the waterwheel drove the smithy hammers or pumped the bellows for the forge fire. Water-powered pounding mills for fulling, a step in the manufacture of cloth, also first appear at this time, so that we are reasonably sure that water-powered hammers or stamps were used in the metallurgical industries by A.D. 1000; the probability is strong that power bellows were also in use by then. Power bellows gradually increased in size and efficiency until, by 1384 at Liège in Flanders, they were producing temperatures high enough to make cast iron in the first known blast furnaces.

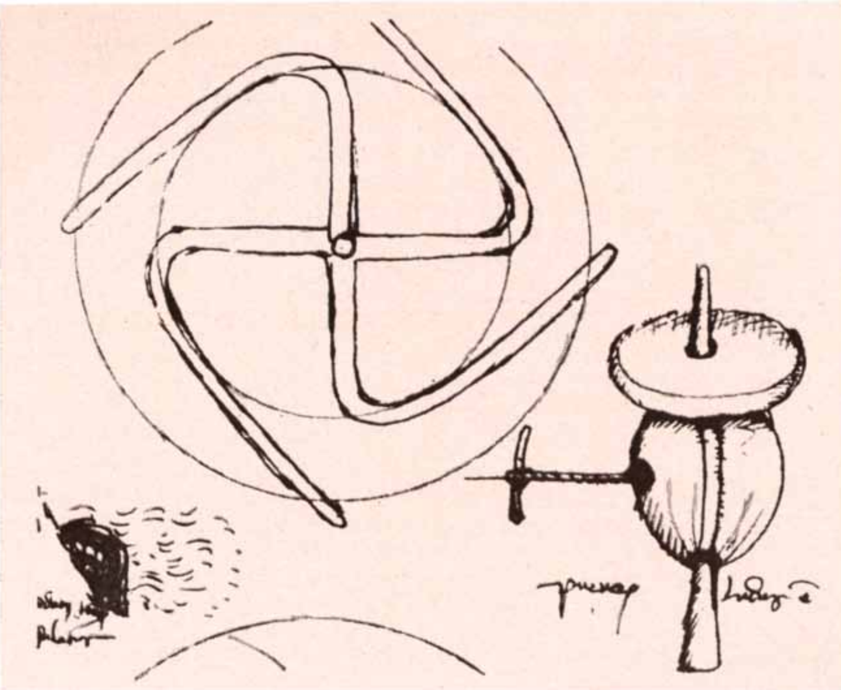
This production of cast iron, the greatest metallurgical development since the discovery of iron itself, qualifies as one of the medieval uses of air that was of immediate importance to Western culture. Although cast iron had been known in China much earlier than the 14th century, most Chinese iron ores contain phosphorus. This inclusion lowers the melting point of the iron so that it can be cast at lower temperatures, but the cast iron that results is a metal of limited versatility. The European blast furnace of the late 14th century could



FIRST WINDMILL, its vanes attached to a vertical axle, was invented somewhere in the Middle East during the 10th century. This is a later model, developed in Europe during the 16th century.



SECOND WINDMILL, with a horizontal axle, was invented independently in the 12th century in the North Sea region of Europe. The one shown is a "tower mill." Only its top is turned to the wind.



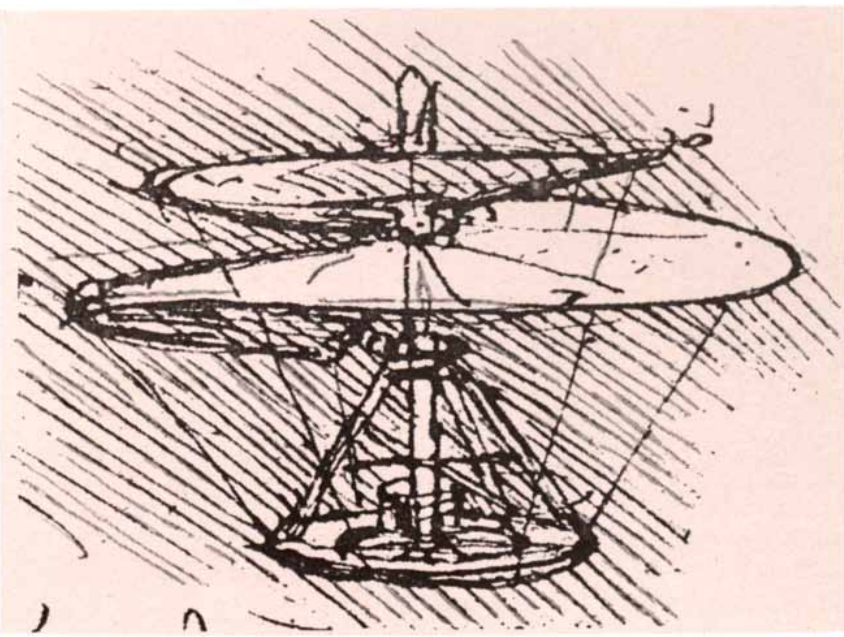
FIRST AIRSCREW was drawn in plan view (*left*) in the notebook of Mariano Taccola, an engineer in Siena in the 15th century. The words under the launcher for the airscrew, sketched in perspective at right, are *puerorum ludus est,* Latin for "[it] is a boys' toy."

smelt superior ores, and its development vastly expanded both production and consumption of iron in the West.

A bellows produces wind. Anyone who watches a hawk soaring can see that its flight involves resistance to the wind. Although at least two Muslims are known to have attempted to fly earlier, it is perhaps not a coincidence that the first European to try it was a younger Anglo-Saxon contemporary of the organ-building Bishop Elfeg who was likewise a Benedictine. Sometime between A.D. 1000 and 1010, Eilmer, a monk of Malmesbury in Wiltshire, built a glider, took off from the abbey's tower and flew 600 feet before crashing and breaking his legs. His own diagnosis of his failure was entirely matter-of-fact: he said that it was because he forgot to put a tail on the rear end of the glider—"*caudam in posteriore parte.*" Eilmer lived to a ripe and respected old age, and his feat was never forgotten, although he had few imitators.

More than two centuries later, to be sure, Friar Roger Bacon wrote that "flying machines can be constructed in which a man...may beat the air with wings like a bird" and even claimed to know the designer of one. But the fact that no one after Eilmer actually tried to fly (before an instance, badly documented, at Perugia in the 15th century) may be more an indication of common sense than of timidity. The human musculature is such that it cannot power birdlike flight. Gliding, moreover, is very nearly suicide in the absence of fairly detailed knowledge of how air currents move. The great development of gliding in the 19th century rests on observations of kites in flight, but the only news of kites received in medieval Europe, where otherwise they were unknown, was tucked away in the Latin version of Marco Polo's memoirs preserved in the cathedral of Toledo. European kites are a 17th-century development and were still something of a novelty in Benjamin Franklin's time.

Medieval Europeans were destined, however, to become increasingly conscious of the properties of air and its role in motion. The great mechanical pioneer of the first century after Christ, Hero of Alexandria, had sketched a little windmill that, he proposed, might operate the pump of a pipe organ [*see illustration on page 94*]. The mechanism is impractical; it had no subsequent influence, and the best modern opinion calls it the armchair invention of a genius. In the 10th century a quite different kind of windmill was produced in eastern Iran or Afghanistan. A vertical axle, fitted with a series of vanes, was set in a millstone; the wind, which in that region blows constantly from one direction, entered the mill through a door placed off-center to expose only the vanes on one side of the axle, causing the millstone to rotate. The Chinese vertical-axle windmills of the 13th century were derived from this source. There is no firm evidence, however, that knowledge of any kind of windmill spread from the Middle East to the other parts of Islam. This is surprising; the dearth of water power in the largely arid Islamic lands might seem to make windmills particularly useful.



LARGER AIRSCREW, designed to lift a man, is shown in a drawing by Leonardo da Vinci, who proposed making it out of starched linen. The lack of an adequate power source barred practical use of airscrews, however, until the internal-combustion engine was developed.

The windmill as we know it, with vanes on a horizontal axle, is seen in the illustration at the right on page 95 (and on the cover of this issue of *Scientific American*). It was invented independently in the North Sea region of Europe by A.D. 1185, probably by applying the principle of Vitruvius' water mill (an invention of classical times that was still in common use and had a horizontal axle) to the harnessing of wind power. The spread of the new machine was explosive: within seven years of its first appearance in Europe the windmill was known in Palestine, where it had been imported by German Crusaders. By the 1190's the Pope was trying to tax windmills—a sure sign of their success.

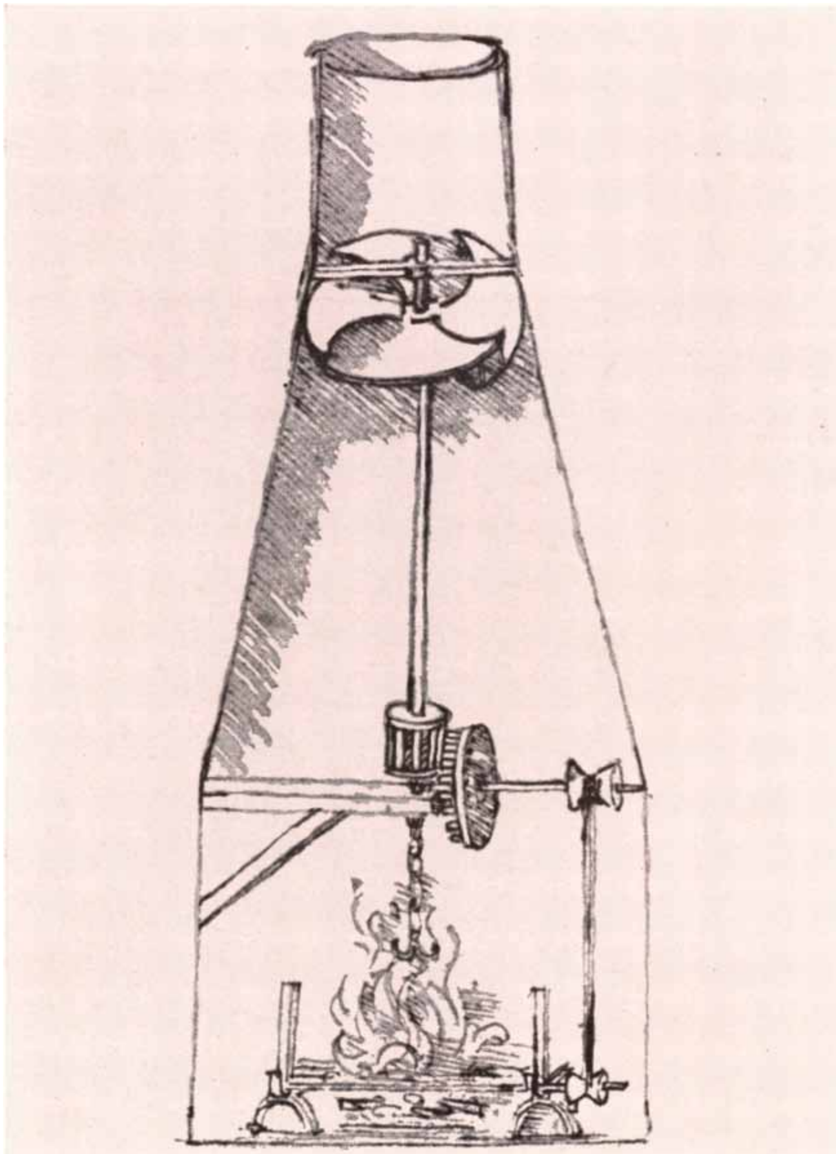
In flat country, where good sites for water mills are scarce, the windmill offered an invaluable new source of mechanical power. By the 13th century, for example, at least 120 windmills stood around Ypres in Flanders. Because their location was not restricted to the banks of streams, windmills came into use to some extent in all parts of Europe. Castles were seldom built directly beside running water; windmills were often installed in castles to produce flour during sieges. Early in the 14th century an English chronicler lamented that the search for long wooden beams suitable for the vanes of windmills was a major cause of deforestation. Dante, in his *Inferno*, was sure that all his readers had seen windmills when he described Satan flailing his arms like "*un molin che il vento gira.*" Don Quixote's astonishment at windmills (and at fulling mills too, as is often forgotten) is one of Cervantes' ways of emphasizing that La Mancha was the backwoods of Spain.

Water mills had appeared in the last years of the Roman Republic. They spread steadily throughout the early Middle Ages until by the 11th century every European community had one. Now, with the diffusion of the windmill, a second big power machine was blanketing Europe. In no other society had the constant presence of such engines been a stimulus to further engineering adventures. The windmill was not only a major new source of power; it was also a prime element in building the technological mentality of our culture.

If moving air can turn axles, then the friction of static air against moving vanes can decelerate them. About 1250, at the court of St. Louis, King of France, an immense illustrated version of the Bible was produced. One of the pictures, illustrating King Hezekiah's dream, shows a large water clock, presumably modeled after a clock in the king's palace in Paris. Every hour on the hour the water clock triggered a mechanical chime driven by a falling weight. To slow the fall of the weight a brake has been provided in the form of whirling vanes. Similar "fan escapements" are found in the striking mechanisms of weight-driven clocks of the 14th century and later.

Early in the next century a variant appears. Someone saw that, if fan vanes on a vertical axle are tilted slightly and the fan is spun with the uptilted edges of the vanes leading, the rotating fan will tend to rise. Such a device is first found, labeled *puerorum ludus* ("boys' toy"), in a manuscript of the 1430's produced by a citizen of Siena, Mariano di Jacopo Taccola, who was the most creative engineer of his generation. It has been stated that this little protohelicopter came to Europe from China, but the evidence for its earlier presence there is not yet firm. We have several other pictures of such aerial tops from later in the 15th century; the fact that technicians other than Taccola were aware of their potential is shown by Leonardo's famous sketch of an airscrew. As in the case of winged flight, however, nothing practical could be achieved until the development of the internal-combustion engine (which, incidentally, traces its ancestry back through the experiments of Denis Papin in 1690 and Christiaan Huygens in 1673 to the invention of the cannon early in the 14th century).

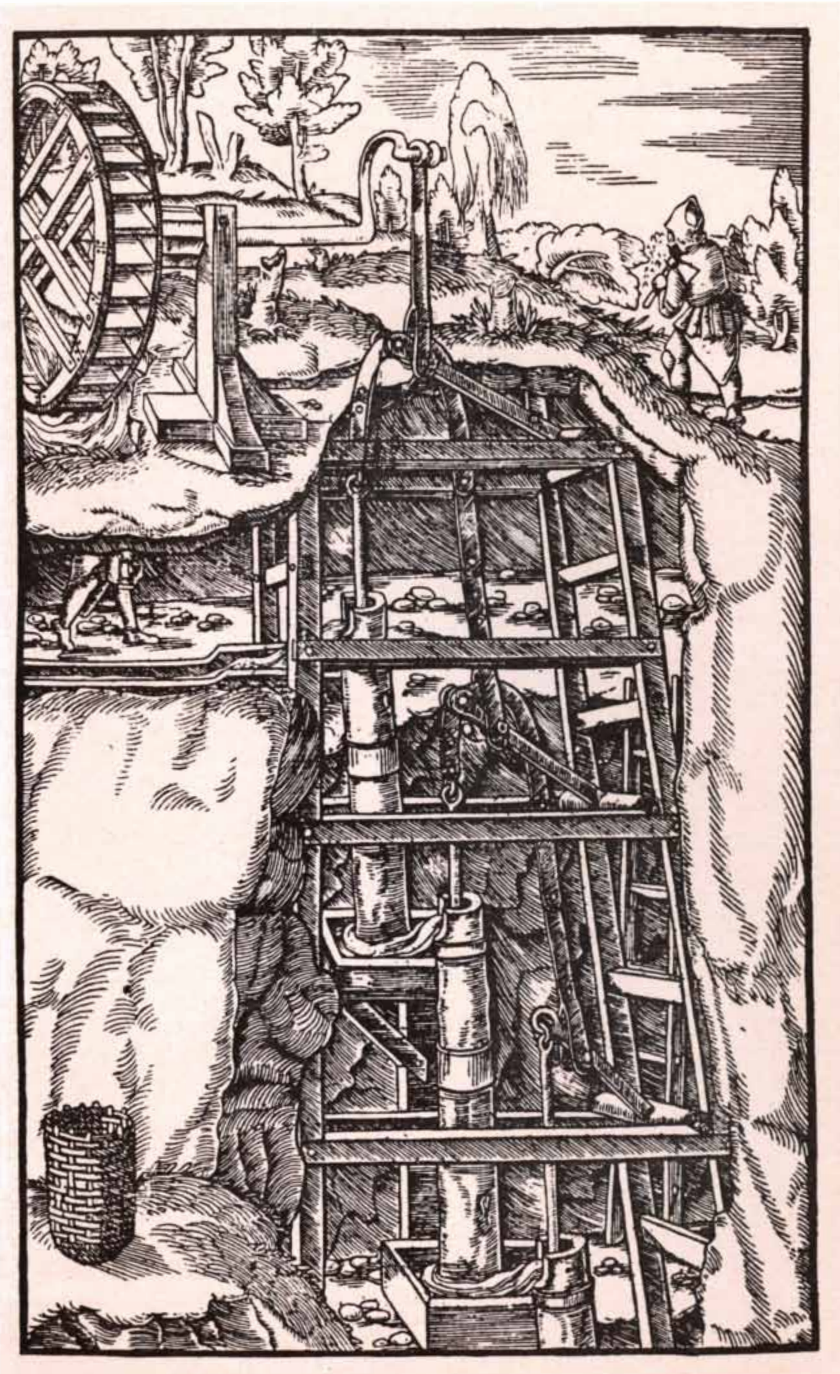
The helicopter toy, boring its way up-



GAS TURBINE applied the principle of the airscrew to a static situation. As another sketch by Leonardo indicates, the flow of hot air up the chimney makes a set of blades rotate, and their motion, transmitted by gears and a belt drive, turns the spit near the fire.

ward through the air, took the initiative. Could anything be done if instead the air passed swiftly upward through a fixed rosette of slightly tilted vanes? In chimneys the hot air rises with some force; late in the 15th century Leonardo gives us our first picture of a roasting spit activated by an air turbine placed in a chimney [*see illustration on preceding page*]. Similar machines are known from other sources shortly thereafter, so that in this case Leonardo was probably recording rather than inventing. These powered spits were elegant in their automatic control; the hotter the fire, the more rapidly the roast rotated.

The uses of the air in the Hellenistic world did not extend to pumps; the Hellenistic pumps were force pumps, which work without the aid of atmospheric pressure. The first evidence of a suction pump, which utilizes the weight of air to raise water, appears by a curious coincidence in the same manuscript by Taccola that contains the first airscrew. The device is still primitive: the piston is raised by a cord and evidently falls simply by gravity; moreover, the compound crank is defective. These faults were soon remedied, and the use of suction pumps spread swiftly, first within Italy and then to the mining districts north of the Alps. Now at last we see an input from the technology of air to the science of air. At this time a vacuum could not be observed in nature. By providing a "laboratory situation," suction pumps did much to stimulate men such as Galileo (and Otto von Guericke, whose demonstration of the vacuum-sealed "Magdeburg hemispheres" astonished the imperial court in 1654) to investigate the phenomenon of variable air pressure.

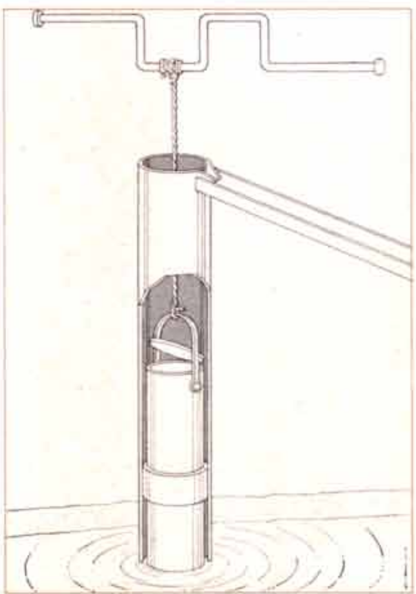


ADVANCED SUCTION PUMP appears in 1556 treatise on mining by Georgius Agricola. A crank, driven by a waterwheel, drives the pistons of a three-stage pump. Water is lifted from one stage to the next until it pours into a trough that leads the water out of the mine.

Another new gadget led to further application of air pressure. The flow of spices to Europe from the Indies, which had been established in classical times, was never seriously interrupted. It is therefore not astonishing that around A.D. 1425 the Malay blowgun reached Italy, accompanied by its native name, *sumpitan* (which, as the Arabic *zabaṭānah,* became successively the Italian *cerbottána* and the English *sarbacane*). As a French manuscript painting of about 1475 shows, the blowgun was used in Europe chiefly for hunting birds. If one could propel a dart with compressed air, why not other things? A Nuremberg picture of 1474 shows the earliest use of compressed air to convey materials: a winehandler is using a special bellows to force wine through a tube from one barrel to another.

To us who see the third millennium approaching and who take moon landings almost for granted, our ancestors' practical applications of the force and substance of air during the five centuries that separate Eilmer's glider in Malmesbury from Leonardo's automated spit may seem rudimentary. Such a judgment commits the intellectual sin of anachronism. To evaluate what those generations of technicians accomplished we must take our historical stance not in 1970 but in 970. Looked at from there, the engineering accomplishments of the later Middle Ages not only are spectacular but also provide the essential basis for what the West has achieved since then. The earlier growth of technology had been steady, but it was incredibly slow by modern standards. Between the seventh and the 10th century the medieval West had taken the initiative in developing a new and more productive agriculture and a superior military technology. Around A.D. 1000 these impulses carried over into engineering. Before that time the Chinese had been the most

COMPRESSED AIR is serving as a propellant, forcing wine through a tube from one barrel to another, in a painting made in Nuremberg in A.D. 1474. Large-scale movements of materials with compressed air had to await the development of better blowers.



PRIMITIVE SUCTION PUMP appears in the same notebook of Mariano Taccola's that shows the first airscrew. This modern drawing is based on his sketch: the piston is raised by a cord and gravity makes it fall.

inventive of the great cultures. By about A.D. 1350, however, Europe began to surpass China in technological innovation. Today's mechanical technology, which aims at the use of natural power and automatic control to save human labor, is the extrapolation of a concerted and unbroken cultural movement that is now some 10 centuries old. The inventory of medieval explorations of the uses of air reviewed here shows one aspect of that concerted thrust in its earlier phases.

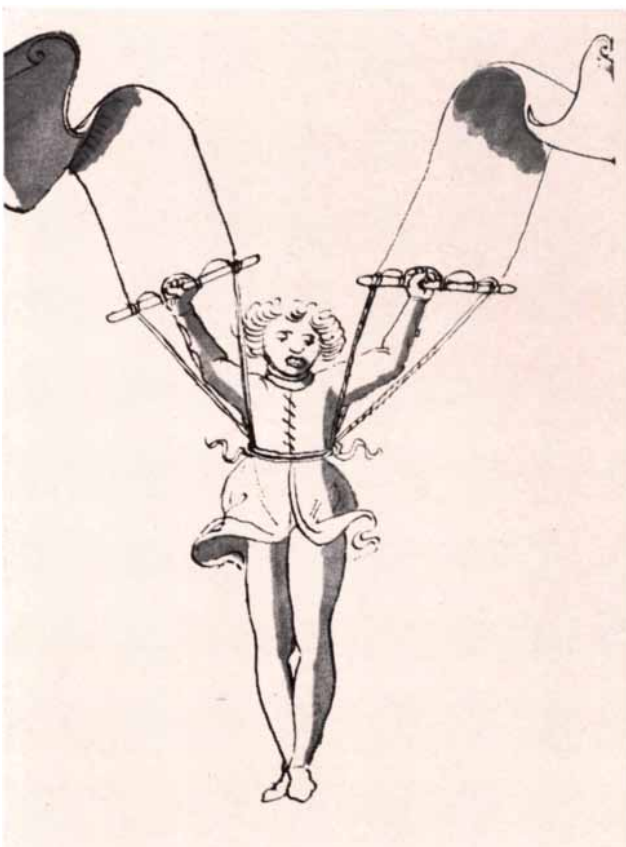
Of the items reviewed here four—the improvement in sails, the development of the blast furnace and the invention of the windmill and the suction pump—were of immediate importance. The elaboration of some of the other innovations took more time. The obstacles in the way of achieving flight are obvious. The large-scale use of compressed air for materials transport had to await more powerful blowers than were then feasible. The failure of medieval engineers to turn all their dreams into realities is less significant than the vigor with which they conceived new technologies. The parachute, a means of using air friction for deceleration, is a case in point.

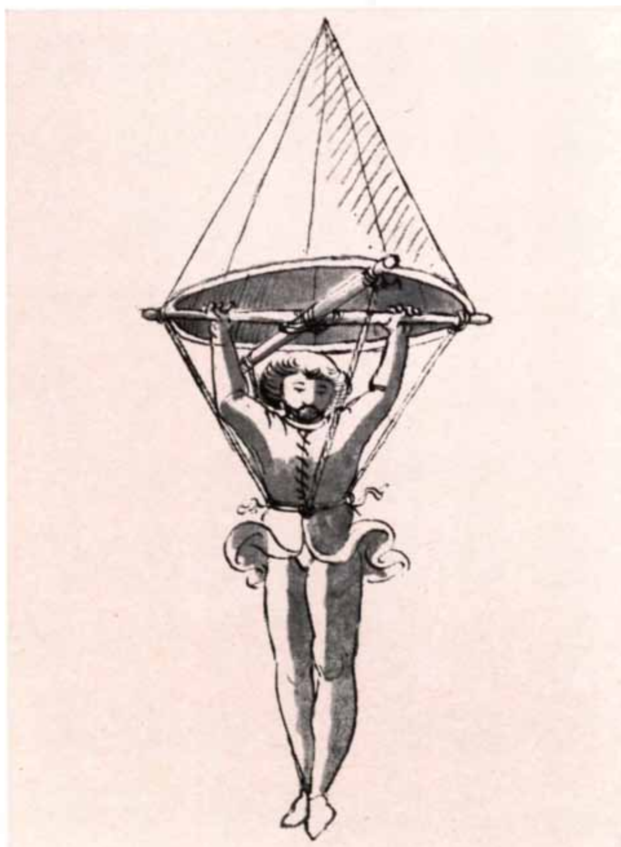
Preserved in the British Museum is the notebook of an anonymous Italian engineer, probably a citizen of Siena, that covers a period during the late 1470's or the early 1480's. On one of its pages a man is pictured jumping through empty air [*see illustration at left below*]. At first glance the expression of his mouth is odd; the reason is that he is gripping a sponge between his teeth to protect his jaws from the shock of landing. All that is braking his fall is a pair of cloth streamers. He looks scared. He should be.

The next few pages of the manuscript show fairly routine devices: derricks, military machines and the like. Our engineer-sketcher, however, is also worried about that jumper. Something better must be done for him. After 21 pages the jumper reappears [*see illustration at right below*]. The sponge is now secured in his teeth by a strap that runs around his head, so that if he cries out in terror he will not drop it. Above him appears a much more efficient, although still far too small, decelerator: a conical parachute. It is the earliest depiction of the device so far discovered.

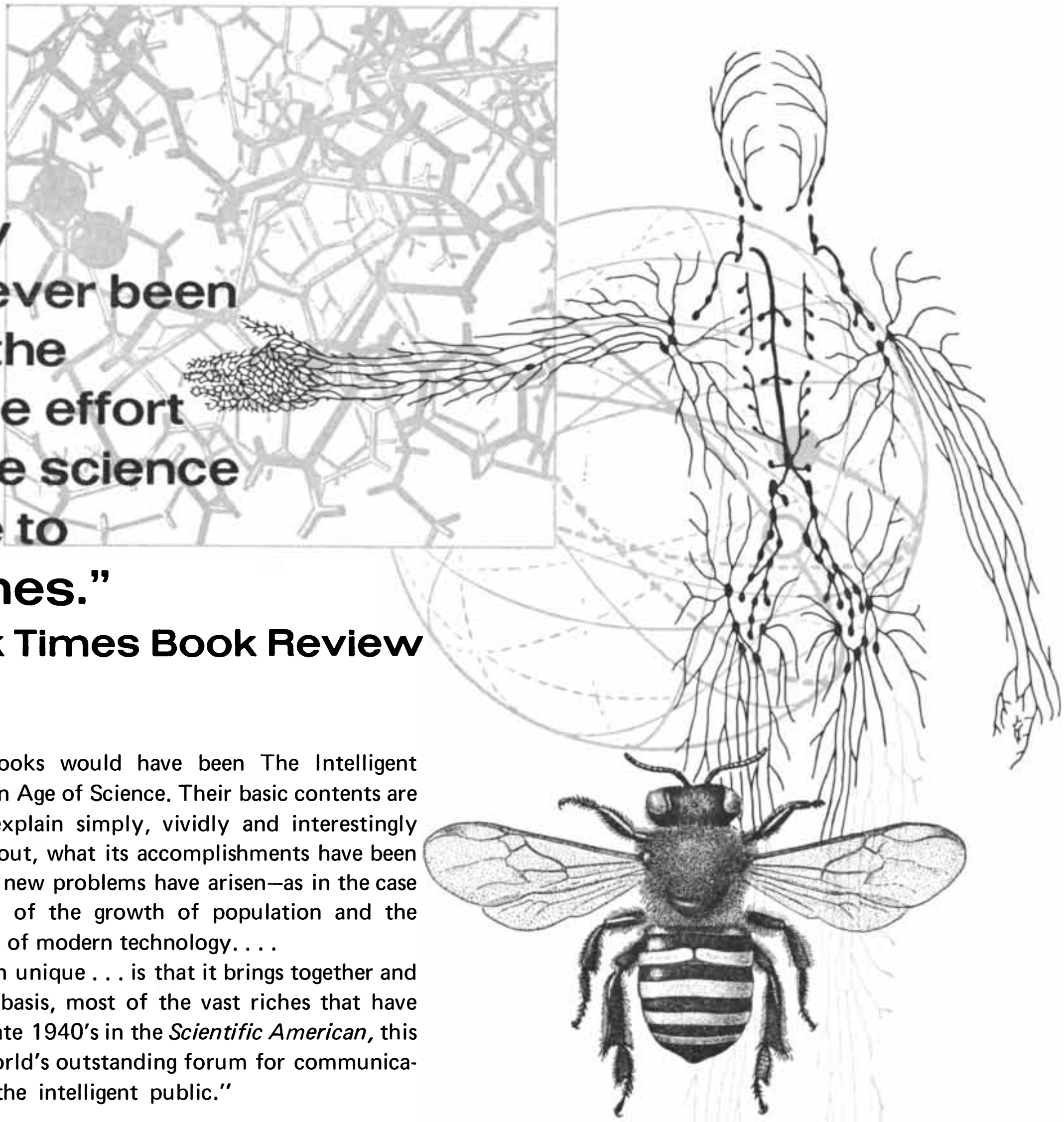
Slightly later Leonardo drew a pyramidal parachute; by the 1480's the idea, if not the thing, was in the air. It reached actual publication in 1615–1616 in a famous book, *New Machines,* by Fausto Veranzio, a bishop in Hungary. Thenceforth everyone concerned with mechanics knew its possibilities. It was not until some 300 years after the parachute's conceptual invention by the anonymous Italian engineer, however, that anybody actually jumped in one. Not until the brothers Montgolfier began ballooning did parachuting become functional; the first actual jump was made in 1783. The notion of the parachute had been available for 10 generations. When it was needed, the notion was there to be applied.

The virtue of early engineers lies not only in what they accomplished but also in what they imagined. In our own time, when the parachute is a familiar adjunct to airplanes and space vehicles, it is a symbol of why we may well respect the creativity of the technicians of centuries long gone. Quite without the aid of science they greatly expanded not only the repertory of engineering but also the Western concept of the scope of technology.





PARACHUTER'S PROGRESS is evident in successive sketches made by an anonymous Italian engineer late in the 15th century. At left the jumper's fall is decelerated only by friction of the air against a pair of cloth streamers. At right the engineer has improved on his original scheme by substituting a conical canopy of cloth for the streamers. The first recorded jump was made in 1783.



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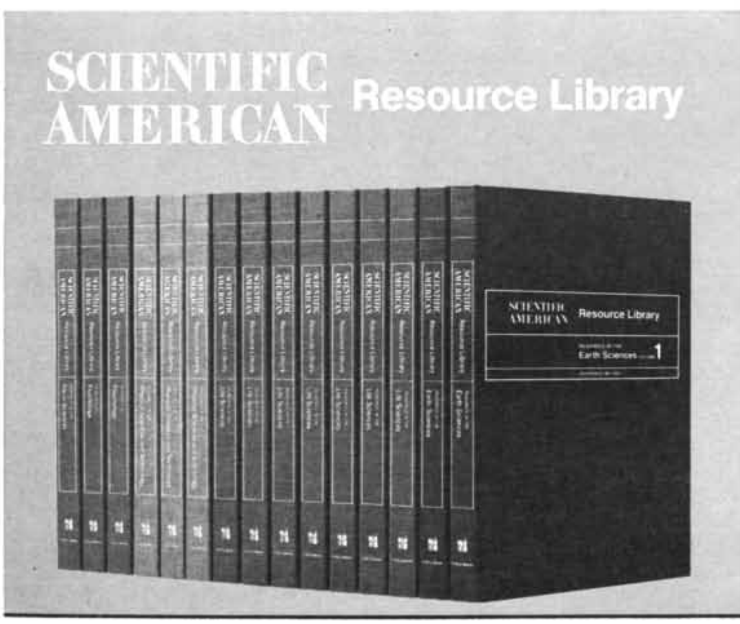

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The Origin of Personality

Children differ in temperament from birth. What is the nature of these temperamental differences, and how do they interact with environmental influences in the formation of personality?

by Alexander Thomas, Stella Chess and Herbert G. Birch

Mothers, nurses and pediatricians are well aware that infants begin to express themselves as individuals from the time of birth. The fact that each child appears to have a characteristic temperament from his earliest days has also been suggested by Sigmund Freud and Arnold Gesell. In recent years, however, many psychiatrists and psychologists appear to have lost sight of this fact. Instead they have tended to emphasize the influence of the child's early environment when discussing the origin of the human personality.

As physicians who have had frequent occasion to examine the family background of disturbed children, we began many years ago to encounter reasons to question the prevailing one-sided emphasis on environment. We found that some children with severe psychological problems had a family upbringing that did not differ essentially from the environment of other children who developed no severe problems. On the other hand, some children were found to be free of serious personality disturbances although they had experienced severe family disorganization and poor parental care. Even in cases where parental mishandling was obviously responsible for a child's personality difficulties there was no consistent or predictable relation between the parents' treatment and the child's specific symptoms. Domineering, authoritarian handling by the parents might make one youngster anxious and submissive and another defiant and antagonistic. Such unpredictability seemed to be the direct consequence of omitting an important factor from the evaluation: the child's own temperament, that is, his own individual style of responding to the environment.

It might be inferred from these opinions that we reject the environmentalist tendency to emphasize the role of the child's surroundings and the influence of his parents (particularly the mother) as major factors in the formation of personality, and that instead we favor the constitutionalist concept of personality's being largely inborn. Actually we reject both the "nurture" and the "nature" concepts. Either by itself is too simplistic to account for the intricate play of forces that form the human character. It is our hypothesis that the personality is shaped by the constant interplay of temperament and environment.

We decided to test this concept by conducting a systematic long-term investigation of the differences in the behavioral reactions of infants. The study would be designed to determine whether or not these differences persist through childhood, and it would focus on how a child's behavioral traits interact with specific elements of his environment. Apart from satisfying scientific curiosity, answers to these questions would help parents and teachers—and psychiatrists—to promote healthy personality development.

After much preliminary exploration we developed techniques for gathering and analyzing information about individual differences in behavioral characteristics in the first few months of life, for categorizing such differences and for identifying individuality at each stage of a child's life. This technique consisted in obtaining detailed descriptions of children's behavior through structured interviews with their parents at regular intervals beginning when the child had reached an age of two to three months. Independent checks by trained observers established that the descriptions of the children's behavior supplied by the parents in these interviews could be accepted as reliable and significant.

Analyzing the data, we identified nine characteristics that could be reliably scored on a three-point scale (medium, high and low): (1) the level and extent of motor activity; (2) the rhythmicity, or degree of regularity, of functions such as eating, elimination and the cycle of sleeping and wakefulness; (3) the response to a new object or person, in terms of whether the child accepts the new experience or withdraws from it; (4) the adaptability of behavior to changes in the environment; (5) the threshold, or sensitivity, to stimuli; (6) the intensity, or energy level, of responses; (7) the child's general mood or "disposition," whether cheerful or given to crying, pleasant or cranky, friendly or unfriendly; (8) the degree of the child's distractibility from what he is doing; (9) the span of the child's attention and his persistence in an activity.

The set of ratings in these nine characteristics defines the temperament, or behavioral profile, of a child, and the profile is discernible even as early as the age of two or three months. We found that the nine qualities could be identified and rated in a wide diversity of population samples we studied: middle-class children, children of working-class Puerto Ricans, mentally retarded children, children born prematurely and children with congenital rubella ("German measles"). Other investigators in the U.S. and abroad have identified the same set of characteristics in children.

Equipped with this means of collecting and analyzing the required data on individual children through standard interviews with their parents, we proceeded to our long-term study of the development of a large group of children. We obtained the willing collaboration of 85 families, with a total of 141 children, who agreed to allow us to follow their children's development from birth over a period of years that by now extends to

HALLIE, a six-month-old experimental subject, is shown in motion picture taken during an observation session. In frames beginning at top left and running downward she pulls at rings hanging above her crib and repeatedly pushes away stuffed animal. She demonstrates a high level of concentration and persistence by rejecting animal each time it is given and continuing to play with the rings.

POSITIVE RESPONSE is displayed by Hallie when she was three months old as she is fed a new food, Cream of Wheat, for the first time. When her mother presents her with a spoonful of the food, she accepts it eagerly, swallows it and unhesitatingly accepts more.

more than a decade. Our parents have cooperated magnificently in all the interviews and tests, and in the 14 years since the study was started only four families (with five children) have dropped out. In order to avoid complicating the study by having to consider a diversity of socioeconomic influences we confined the study to a homogeneous group, consisting mainly of highly educated families in the professions and business occupations.

We have observed the children's development throughout their preschool period and their years in nursery and elementary school. Their parents have been interviewed at frequent intervals, so that descriptions of the children's behavior have been obtained while the parents' memory of it was still fresh. The interviews have focused on factual details of how the children behaved in specific situations, avoiding subjective interpretations as much as possible. We have supplemented the parental interviews with direct observation and with information obtained from the children's teachers. The children have also been examined with various psychological tests. Youngsters who have shown evidence of behavioral disturbances have received a complete psychiatric examination. The detailed behavioral data collected on all the children have been analyzed both in statistical and in descriptive terms.

Our preliminary exploration had already answered our first question: Children do show distinct individuality in temperament in the first weeks of life, independently of their parents' handling or personality style. Our long-term study has now established that the original characteristics of temperament tend to persist in most children over the years. This is clearly illustrated by two striking examples. Donald exhibited an extremely high activity level almost from birth. At three months, his parents reported, he wriggled and moved about a great deal while asleep in his crib. At six months he "swam like a fish" while being bathed. At 12 months he still squirmed constantly while he was being dressed or washed. At 15 months he was "very fast and busy"; his parents found themselves "always chasing after him." At two years he was "constantly in motion, jumping and climbing." At three he would "climb like a monkey and run like an unleashed puppy." In kindergarten his teacher reported humorously that he would "hang from the walls and climb on the ceiling." By the time he was seven Donald was encountering difficulty in school because he was unable to sit still long enough to learn anything and disturbed the other children by moving rapidly about the classroom.

Clem exemplifies a child who scored high in intensity of reaction. At four and a half months he screamed every time he was bathed, according to his parents' report. His reactions were "not discriminating—all or none." At six months during feeding he screamed "at the sight of the spoon approaching his mouth." At nine and a half months he was generally "either in a very good mood, laughing or chuckling," or else screaming. "He laughed so hard playing peekaboo he got hiccups." At two years his parents reported: "He screams bloody murder when he's being dressed." At seven they related: "When he's frustrated, as for example when he doesn't hit a ball very far, he stomps around, his voice goes up to its highest level, his eyes get red and occasionally fill with tears. Once he went up to his room when this occurred and screamed for half an hour."

Of course a child's temperament is not immutable. In the course of his development the environmental circumstances may heighten, diminish or otherwise modify his reactions and behavior. For example, behavior may become routinized in various areas so that the basic temperamental characteristics are no longer evident in these situations. Most children come to accept and even take pleasure in the bath, whatever their initial reactions may have been. The characteristics usually remain present, however, and may assert themselves in new situations even in the form of an unexpected and mystifying reaction. An illustration is the case of a 10-year-old girl who had been well adjusted to school. Entering the fifth grade, Grace was transferred from a small school to a large new one that was strongly departmentalized and much more formal. The change threw her into a state of acute fear and worry. Her parents were

NEGATIVE RESPONSE is demonstrated by Hallie's younger brother, Russ, during his first exposure to a cereal at three months of age. He refuses to swallow the new food, spits it out, pushes the spoon away, grimaces and tilts his head away from the spoon.

puzzled, because Grace had many friends and had been doing very well in her studies. On reviewing her history, however, we found that she had shown withdrawal reactions to new situations during infancy and also on entrance into kindergarten and the first and second grades. Her parents and Grace had forgotten about these early reactions, because from the third grade on she was entirely happy in school. In the light of the early history it now became apparent that Grace's fear at the transfer to the new school, confronting her with a new scholastic setup, new fellow-students and a new level of academic demand, arose from her fundamental tendency to withdraw from new situations and to be slow to adapt to them.

Not all the children in our study have shown a basic constancy of temperament. In some there have apparently been changes in certain characteristics as time has passed. We are analyzing the data in these cases to try to determine if changes in the children's life situations or in specific stresses are responsible for the apparent fluctuations in temperament. We may find that inconsistency in temperament is itself a basic characteristic in some children.

When we analyzed the behavioral profiles of the children in an endeavor to find correlations among the nine individual attributes, we found that certain characteristics did cluster together. The clusters defined three general types of temperament (although some of the children did not fit into any of the three).

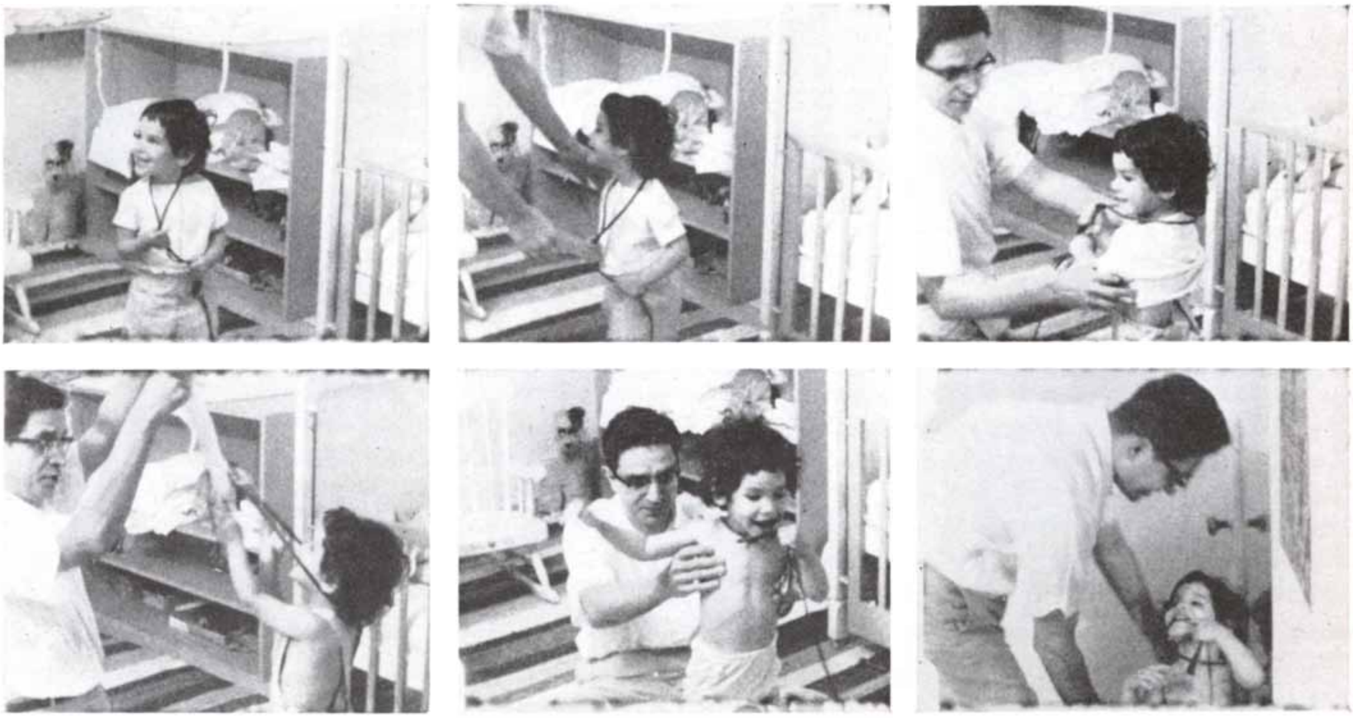
One type is characterized by positiveness in mood, regularity in bodily functions, a low or moderate intensity of reaction, adaptability and a positive approach to, rather than withdrawal from, new situations. In infancy these children quickly establish regular sleeping and feeding schedules, are generally cheerful and adapt quickly to new routines, new foods and new people. As they grow older they learn the rules of new games quickly, participate readily in new activities and adapt easily to school. We named this group the "easy children," because they present so few problems in care and training. Approximately 40 percent of the children in our total sample could be placed in this category.

In contrast, we found another constellation of characteristics that described "difficult children." These children are irregular in bodily functions, are usually intense in their reactions, tend to withdraw in the face of new stimuli, are slow to adapt to changes in the environment and are generally negative in mood. As infants they are often irregular in feeding and sleeping, are slow to accept new foods, take a long time to adjust to new routines or activities and tend to cry a great deal. Their crying and their laughter are characteristically loud. Frustration usually sends them into a violent tantrum. These children are, of course, a trial to their parents and require a high degree of consistency and tolerance in their upbringing. They comprised about 10 percent of the children in our sample.

The third type of temperament is displayed by those children we call "slow to warm up." They typically have a low activity level, tend to withdraw on their first exposure to new stimuli, are slow to adapt, are somewhat negative in mood and respond to situations with a low intensity of reaction. They made up 15 percent of the population sample we studied. Hence 65 percent of the children could be described as belonging to one or another of the three categories we were able to define; the rest had mixtures of traits that did not add up to a general characterization.

Among the 141 children comprising our total sample, 42 presented behavioral problems that called for psychiatric attention. Not surprisingly, the group of "difficult children" accounted for the largest proportion of these cases, the "slow to warm up children" for the next-largest proportion and the "easy children" for the smallest proportion. About 70 percent of the "difficult children" developed behavioral problems, whereas only 18 percent of the "easy children" did so.

In general easy children respond favorably to various child-rearing styles. Under certain conditions, however, their ready adaptability to parental handling may itself lead to the development of a behavioral problem. Having adapted readily to the parents' standards and expectations early in life, the child on moving into the world of his peers and



TWO YEARS OLD, Hallie plays with her father as he tries to change her clothes. He gets shirt off after struggling to lift it over her head, but she holds on with cord. She runs away, provoking chase, and tries to escape as he buttons her shirt. Hallie displays

school may find that the demands of these environments conflict sharply with the behavior patterns he has learned at home. If the conflict between the two sets of demands is severe, the child may be unable to make an adaptation that reconciles the double standard.

The possible results of such a dissonance are illustrated in the case of an "easy child" we shall call Isobel. Reared by parents who placed great value on individuality, imagination and self-expression, she developed these qualities to a high degree. When she entered school, however, her work fell far below her intellectual capabilities. She had difficulties not only in learning but also in making friends. It was found that the problems arose from her resistance to taking instruction from her teacher and to accepting her schoolmates' preferences in play. Once the nature of the conflict was recognized it was easily remedied in this case. We advised the parents to combine their encouragement of Isobel's assertions of individuality with efforts to teach her how to join constructively in activities with her teacher and schoolmates. The parents adopted this strategy, and within six months Isobel began to function well in school life.

In the case of difficult children the handling problem is present from the outset. The parents must cope with the child's irregularity and the slowness with which he adapts in order to establish conformity to the family's rules of living. If the parents are inconsistent, impatient or punitive in their handling of the child, he is much more likely to react negatively than other children are. Only by exceptionally objective, consistent treatment, taking full account of the child's temperament, can he be brought to get along easily with others and to learn appropriate behavior. This may take a long time, but with skillful handling such children do learn the rules and function well. The essential requirement is that the parents recognize the need for unusually painstaking handling; tactics that work well with other children may fail for the difficult child.

For children in the "slow to warm up" category the key to successful development is allowing the child to adapt to the environment at his own pace. If the teacher or parents of such a child pressure him to move quickly into new situations, the insistence is likely to intensify his natural tendency to withdraw. On the other hand, he does need encouragement and opportunity to try new experiences. Bobby was a case in point. His parents never encouraged him to participate in anything new; they simply withdrew things he did not like. When, as an infant, he rejected a new food by letting it

TYPE OF CHILD	ACTIVITY LEVEL The proportion of active periods to inactive ones.	RHYTHMICITY Regularity of hunger, excretion, sleep and wakefulness.	DISTRACTIBILITY The degree to which extraneous stimuli alter behavior.
"EASY"	VARIES	VERY REGULAR	VARIES
"SLOW TO WARM UP"	LOW TO MODERATE	VARIES	VARIES
"DIFFICULT"	VARIES	IRREGULAR	VARIES

TEMPERAMENT of a child allows him to be classified as "easy," "slow to warm up" or "difficult" according to how he rates in certain key categories in the authors' nine-point

many temperamental characteristics such as intensity, positive mood and high activity.

dribble out of his mouth, they eliminated it from his diet. When he backed away from other children in the playground, they kept him at home. By the age of 10 Bobby was living on a diet consisting mainly of hamburgers, applesauce and medium-boiled eggs, and in play he was a "loner." Any activity that required exposure to new people or new demands was distasteful or even impossible for him. Yet he was adept and took pleasure in activities he could pursue by himself and at his own speed.

In general our studies indicate that a demand that conflicts excessively with any temperamental characteristics and capacities is likely to place a child under heavy and even unbearable stress. This means that parents and teachers need to recognize what a specific child can and cannot do. A child with a high activity level, for example, should not be required to sit still through an eight-hour automobile trip; frequent stops should be made to allow him to run around and give vent to his energy. A persistent child who does not like to be distracted from a project should not be expected to come running when he is called unless he has been told in advance how much time he will have before he is called.

Obviously a detailed knowledge of a child's temperamental characteristics can be of great help to parents in handling the child and avoiding the development of behavioral problems. A highly adaptable child can be expected to accept new foods without resistance and even welcome them. On the other hand, a nonadaptable, intense child may need to have the same food offered at each meal for several days until he comes to accept it; if the mother takes away a rejected food, tries it again some weeks later and again retreats in the face of protests, the child simply learns that by fussing enough he will have his way. An adaptable child who is caught sticking things into electric sockets may need only one lecture on the danger to give up this practice; an easily distractible child may merely need to have his attention diverted to some other activity; a persistent child may have to be removed bodily from the hazard.

Understanding a child's temperament is equally crucial in the school situation. His temperamental traits affect both his approach to a learning task and the way he interacts with his teacher and classmates. If the school's demands on him go against the grain of these traits, learning may be difficult indeed. Hence the teacher has a need to know not only the child's capacities for learning but also his temperamental style.

A pupil who wriggles about a great deal, plays continually with his pencils and other objects and involves himself in activities with the student next to him—in short, a child with a high activity level—obviously requires special handling. If the teacher decides the child does not want to learn and treats him accordingly, the youngster is apt to conclude that he is stupid or unlikable and react with even worse behavior. The teacher is best advised to avoid expressions of annoyance and to provide the child with constructive channels for his energy, such as running necessary errands, cleaning the blackboard and so on. Similarly, a "slow to warm up" child requires patience, encouragement and repeated exposure to a learning task until he becomes familiar with it and comfortable in attacking it. Children with the "difficult" constellation of traits of course present the most taxing problem. They respond poorly to a permissive, *laissez faire* attitude in the teacher and angrily to learning tasks they cannot master immediately. The teacher needs to be firm and patient; once the child has been tided over the period (which may be long) of learning rules or becoming familiar with a new task, he will function well and confidently. *Laissez faire* treatment is also detrimental for youngsters who are low in persistence and easily distracted from their work. Such a child will do poorly if few demands are made and little achievement is expected of him. He must be required to function up to his abilities.

The paramount conclusion from our studies is that the debate over the relative importance of nature and nurture only confuses the issue. What is important is the interaction between the two—between the child's own character-

APPROACH WITHDRAWAL	ADAPTABILITY	ATTENTION SPAN AND PERSISTENCE	INTENSITY OF REACTION	THRESHOLD OF RESPONSIVENESS	QUALITY OF MOOD
The response to a new object or person.	The ease with which a child adapts to changes in his environment.	The amount of time devoted to an activity, and the effect of distraction on the activity.	The energy of response, regardless of its quality or direction.	The intensity of stimulation required to evoke a discernible response.	The amount of friendly, pleasant, joyful behavior as contrasted with unpleasant, unfriendly behavior.
SITIVE APPROACH	VERY ADAPTABLE	HIGH OR LOW	LOW OR MILD	HIGH OR LOW	POSITIVE
TIAL WITHDRAWAL	SLOWLY ADAPTABLE	HIGH OR LOW	MILD	HIGH OR LOW	SLIGHTLY NEGATIVE
WITHDRAWAL	SLOWLY ADAPTABLE	HIGH OR LOW	INTENSE	HIGH OR LOW	NEGATIVE

personality index (*color*). The categories are only a general guide to temperament. Of the 141 subjects 65 percent could be categorized, but 35 percent displayed a mixture of traits. Such a child might, for example, be rated "easy" in some ways and "difficult" in others.

TEMPERAMENTAL QUALITY	RATING	2 MONTHS	6 MONTHS
ACTIVITY LEVEL	HIGH	Moves often in sleep. Wriggles when diaper is changed.	Tries to stand in tub and splashes. Bounces in crib. Crawls after dog.
	LOW	Does not move when being dressed or during sleep.	Passive in bath. Plays quietly in crib and falls asleep.
RHYTHMICITY	REGULAR	Has been on four-hour feeding schedule since birth. Regular bowel movement.	Is asleep at 6:30 every night. Awakes at 7:00 A.M. Food intake is constant.
	IRREGULAR	Awakes at a different time each morning. Size of feedings varies.	Length of nap varies; so does food intake.
DISTRACTIBILITY	DISTRACTIBLE	Will stop crying for food if rocked. Stops fussing if given pacifier when diaper is being changed.	Stops crying when mother sings. Will remain still while clothing is changed if given a toy.
	NOT DISTRACTIBLE	Will not stop crying when diaper is changed. Fusses after eating, even if rocked.	Stops crying only after dressing is finished. Cries until given bottle.
APPROACH/WITHDRAWAL	POSITIVE	Smiles and licks washcloth. Has always liked bottle.	Likes new foods. Enjoyed first bath in a large tub. Smiles and gurgles.
	NEGATIVE	Rejected cereal the first time. Cries when strangers appear.	Smiles and babbles at strangers. Plays with new toys immediately.
ADAPTABILITY	ADAPTIVE	Was passive during first bath; now enjoys bathing. Smiles at nurse.	Used to dislike new foods; now accepts them well.
	NOT ADAPTIVE	Still startled by sudden, sharp noise. Resists diapering.	Does not cooperate with dressing. Fusses and cries when left with sitter.
ATTENTION SPAN AND PERSISTENCE	LONG	If soiled, continues to cry until changed. Repeatedly rejects water if he wants milk.	Watches toy mobile over crib intently. "Coos" frequently.
	SHORT	Cries when awakened but stops almost immediately. Objects only mildly if cereal precedes bottle.	Sucks pacifier for only a few minutes and spits it out.
INTENSITY OF REACTION	INTENSE	Cries when diapers are wet. Rejects food vigorously when satisfied.	Cries loudly at the sound of thunder. Makes sucking movements when vitamins are administered.
	MILD	Does not cry when diapers are wet. Whimpers instead of crying when hungry.	Does not kick often in tub. Does not smile. Screams and kicks when temperature is taken.
THRESHOLD OF RESPONSIVENESS	LOW	Stops sucking on bottle when approached.	Refuses fruit he likes when vitamins are added. Hides head from bright ligh
	HIGH	Is not startled by loud noises. Takes bottle and breast equally well.	Eats everything. Does not object to diapers being wet or soiled.
QUALITY OF MOOD	POSITIVE	Smacks lips when first tasting new food. Smiles at parents.	Plays and splashes in bath. Smiles at everyone.
	NEGATIVE	Fusses after nursing. Cries when carriage is rocked.	Cries when taken from tub. Cries when given food she does not like.

BEHAVIOR of a child reveals that he has a distinct temperament early in life. These reports taken from interviews with the parents of the children studied by the authors show that temperamental differences are apparent when a child is only two months old. As a child grows his temperament tends to remain constant in quality: if he wriggles while his diaper is being changed at two months,

istics and his environment. If the two influences are harmonized, one can expect healthy development of the child; if they are dissonant, behavioral problems are almost sure to ensue.

It follows that the pediatrician who undertakes to supervise the care of a newborn child should familiarize himself with his young patient's temperamental as well as physical characteristics. He will then be able to provide the parents with appropriate advice on weaning, toilet training and the handling of other needs as the child develops. Similarly, if a behavioral disorder arises, the psychiatrist will need to understand both the child's temperament and the environmental demands in conflict with it in order to find a helpful course of action. His function then will often be to guide rather than "treat" the parents.

1 YEAR	2 YEARS	5 YEARS	10 YEARS
alks rapidly. Eats eagerly. Climbs into erything.	Climbs furniture. Explores. Gets in and out of bed while being put to sleep.	Leaves table often during meals. Always runs.	Plays ball and engages in other sports. Cannot sit still long enough to do homework.
ıishes bottle slowly. Goes to sleep sily. Allows nail-cutting without ssing.	Enjoys quiet play with puzzles. Can listen to records for hours.	Takes a long time to dress. Sits quietly on long automobile rides.	Likes chess and reading. Eats very slowly.
ıps after lunch each day. Always nks bottle before bed.	Eats a big lunch each day. Always has a snack before bedtime.	Falls asleep when put to bed. Bowel movement regular.	Eats only at mealtimes. Sleeps the same amount of time each night.
ll not fall asleep for an hour or more. ves bowels at a different time each y.	Nap time changes from day to day. Toilet training is difficult because bowel movement is unpredictable.	Food intake varies; so does time of bowel movement.	Food intake varies. Falls asleep at a different time each night.
ies when face is washed unless it is ade into a game.	Will stop tantrum if another activity is suggested.	Can be coaxed out of forbidden activity by being led into something else.	Needs absolute silence for homework. Has a hard time choosing a shirt in a store because they all appeal to him.
ies when toy is taken away and ects substitute.	Screams if refused some desired object. Ignores mother's calling.	Seems not to hear if involved in favorite activity. Cries for a long time when hurt.	Can read a book while television set is at high volume. Does chores on schedule.
proaches strangers readily. Sleeps ell in new surroundings.	Slept well the first time he stayed overnight at grandparents' house.	Entered school building unhesitatingly. Tries new foods.	Went to camp happily. Loved to ski the first time.
ffened when placed on sled. Will not ep in strange beds.	Avoids strange children in the playground. Whimpers first time at beach. Will not go into water.	Hid behind mother when entering school.	Severely homesick at camp during first days. Does not like new activities.
as afraid of toy animals at first; now ays with them happily.	Obeys quickly. Stayed contentedly with grandparents for a week.	Hesitated to go to nursery school at first; now goes eagerly. Slept well on camping trip.	Likes camp, although homesick during first days. Learns enthusiastically.
ntinues to reject new foods each e they are offered.	Cries and screams each time hair is cut. Disobeys persistently.	Has to be hand led into classroom each day. Bounces on bed in spite of spankings.	Does not adjust well to new school or new teacher; comes home late for dinner even when punished.
ays by self in playpen for more than hour. Listens to singing for long riods	Works on a puzzle until it is completed. Watches when shown how to do something.	Practiced riding a two-wheeled bicycle for hours until he mastered it. Spent over an hour reading a book.	Reads for two hours before sleeping. Does homework carefully.
ses interest in a toy after a few nutes. Gives up easily if she falls ile attempting to walk.	Gives up easily if a toy is hard to use. Asks for help immediately if undressing becomes difficult.	Still cannot tie his shoes because he gives up when he is not successful. Fidgets when parents read to him.	Gets up frequently from homework for a snack. Never finishes a book.
ughs hard when father plays roughly. eamed and kicked when temperature s taken.	Yells if he feels excitement or delight. Cries loudly if a toy is taken away.	Rushes to greet father. Gets hiccups from laughing hard.	Tears up an entire page of homework if one mistake is made. Slams door of room when teased by younger brother.
es not fuss much when clothing is lled on over head.	When another child hit her, she looked surprised, did not hit back.	Drops eyes and remains silent when given a firm parental "No." Does not laugh much.	When a mistake is made in a model airplane, corrects it quietly. Does not comment when reprimanded.
its out food he does not like. Giggles en tickled.	Runs to door when father comes home. Must always be tucked tightly into bed.	Always notices when mother puts new dress on for first time. Refuses milk if it is not ice-cold.	Rejects fatty foods. Adjusts shower until water is at exactly the right temperature.
ts food he likes even if mixed with iked food. Can be left easily with angers.	Can be left with anyone. Falls to sleep easily on either back or stomach.	Does not hear loud, sudden noises when reading. Does not object to injections.	Never complains when sick. Eats all foods.
es bottle; reaches for it and smiles. ughs loudly when playing peekaboo.	Plays with sister; laughs and giggles. Smiles when he succeeds in putting shoes on.	Laughs loudly while watching television cartoons. Smiles at everyone.	Enjoys new accomplishments. Laughs when reading a funny passage aloud.
es when given injections. Cries when alone.	Cries and squirms when given haircut. Cries when mother leaves.	Objects to putting boots on. Cries when frustrated.	Cries when he cannot solve a homework problem. Very "weepy" if he does not get enough sleep.

his high activity level is likely to be expressed at one year through eager eating and a tendency "to climb into everything." A five-year-old child who behaved quietly in infancy may dress slowly and be able to sit quietly and happily during long automobile rides. Color indicates those temperamental characteristics that are crucial to classifying a child as "easy," "slow to warm up" and "difficult."

Most parents, once they are informed of the facts, can change their handling to achieve a healthier interaction with the child.

Theory and practice in psychiatry must take into full account the individual and his uniqueness: how children differ and how these differences act to influence their psychological growth. A given environment will not have the identical functional meaning for all children. Much will depend on the temperamental makeup of the child. As we learn more about how specific parental attitudes and practices and other specific factors in the environment of the child interact with specific temperamental, mental and physical attributes of individual children, it should become considerably easier to foster the child's healthy development.

MATHEMATICAL GAMES

Backward run numbers, letters, words and sentences until boggles the mind

by Martin Gardner

A palindrome is usually defined as a word, sentence or set of sentences that spell the same backward as forward. The term is also applied to integers that are unchanged when they are reversed. Both types of palindrome have long interested those who amuse themselves with number and word play, perhaps because of a deep, half-unconscious aesthetic pleasure in the kind of symmetry palindromes possess. Palindromes have their analogues in other fields: melodies that are the same backward, paintings and designs with mirror-reflection symmetry, the bilateral symmetry of animals and man, and so on. This month we shall restrict our attention to number and language palindromes and consider some entertaining new developments in both fields.

An old palindrome conjecture of unknown origin (there are references to it in publications of the 1930's) is as follows. Start with any positive integer. Reverse it and add the two numbers. This procedure is repeated with the sum to obtain a second sum, and the process continues until a palindromic sum is obtained. The conjecture is that a palindrome always results after a finite number of additions. For example, 68 generates a palindrome in three steps:

$$\begin{array}{r} 68 \\ +\underline{86} \\ 154 \\ +\underline{451} \\ 605 \\ +\underline{506} \\ 1{,}111 \end{array}$$

For all two-digit numbers it is obvious that if the sum of their digits is less than 10, the first step gives a two-digit palindrome. If their digits add to 10, 11, 12, 13, 14, 15, 16 or 18, a palindrome results after 2, 1, 2, 2, 3, 4, 6, 6 steps respectively. As Angela Dunn points out in *Mathematical Bafflers* (McGraw-Hill, 1964), the exceptions are numbers whose two digits add to 17. Only 89 (or its reversal, 98) meets this proviso. Starting with either number does not produce a palindrome until the 24th operation results in 8,813,200,023,188.

The conjecture was widely regarded as being true until recently, although no one had succeeded in proving it. Charles W. Trigg, a California mathematician well known for his work on recreational problems, examined the conjecture more carefully in his article "Palindromes by Addition" (*Mathematics Magazine*, January, 1967). He found 249 integers smaller than 10,000 that failed to generate a palindrome after 100 steps. The smallest such number, 196, was carried to 4,147 steps by Donald D. Wall of Bethesda, Md., who used a computer. No palindromic sum appeared. Trigg believes the conjecture to be false. (The number 196 is the square of 14, but this is probably an irrelevant fact.) Aside from the 249 exceptions all integers less than 10,000, except 89 and its reversal, produce a palindrome in fewer than 24 steps. The largest palindrome, 16,668,488,486,661, is generated by 6,999 (or its reversal) and 7,998 (or its reversal) in 20 steps.

As far as I know the conjecture has not been established for any number system, and has been proved false only in the binary system. The smallest binary counterexample is 10110 (or 22 in the decimal system). After four steps the sum is 10110100, after eight steps it is 1011101000, after 12 steps it is 101111010000. Every fourth step increases by one digit each of the two sequences of underlined digits. Brother Alfred Brousseau, in "Palindromes by Addition in Base Two" (*Mathematics Magazine*, November, 1969), proves that this asymmetric pattern repeats indefinitely. He also found other repeating asymmetric patterns for larger binary numbers.

There is a small but growing literature on the properties of palindromic prime numbers and conjectures about them. Apparently there is an infinity of such primes, although I have not been able to discover if this actually has been proved. It is not hard to show, however, that a palindromic prime, with the exception of 11, must have an odd number of digits. Can the reader do this before a simple proof is given next month? Norman T. Gridgeman of Ottawa has conjectured that there is an infinity of prime pairs of the form 30,103–30,203 and 9,931,399–9,932,399 in which all digits are alike except the middle digits, which differ by one, but Gridgeman's guess is far from proved.

Gustavus J. Simmons, a mathematician with Rolamite Inc. in Albuquerque, N.M., has a fascinating article on "Palindromic Powers" in the *Journal of Recreational Mathematics* for April. After showing that the probability of a randomly selected integer being palindromic approaches zero as the number of digits in the integer increases, Simmons examines square numbers and finds them much richer than randomly chosen integers in palindromes. There is an infinity of palindromic squares, most of which, it seems, have square roots that also are palindromes. (The smallest nonpalindromic root is 26.) Cubes too are unusually rich in palindromes. A computer check on all cubes less than 2.8×10^{14} turned up a truly astonishing fact. The only palindromic cube with a nonpalindromic cube root, among the cubes examined by Simmons, is 10,662,526,601. Its cube root, 2,201, had been noticed earlier by Trigg, who reported in 1961 that it was the only nonpalindrome with a palindromic cube less than 1,953,125,000,000. It is not yet known if 2,201 is the only integer with this property.

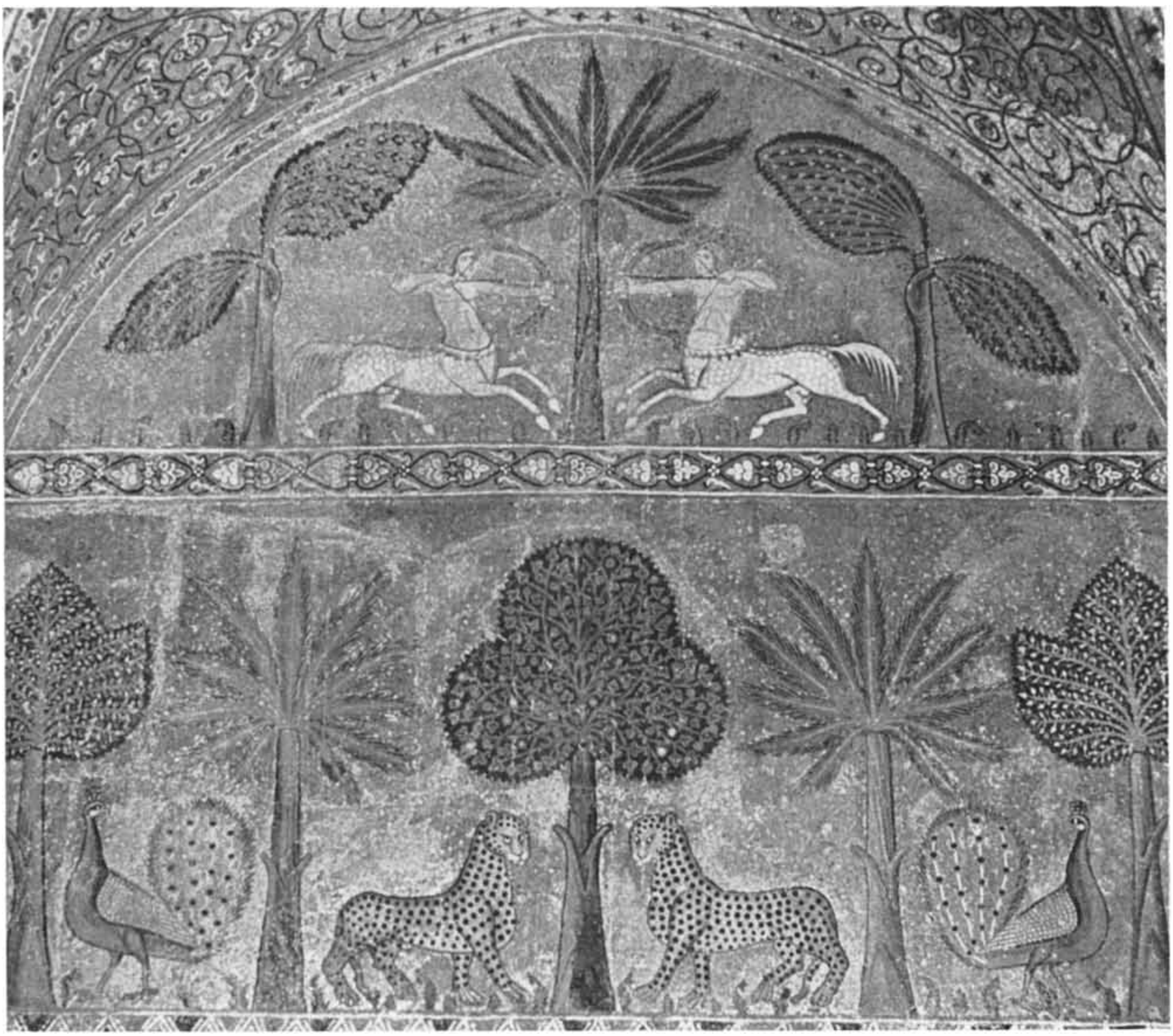
Simmons' computer search of palindromic fourth powers, to the same limit as his search of cubes, failed to uncover a single palindromic fourth power whose fourth root was not a palindrome of the general form 10...01. For powers five through 10 the computer found no palindromes at all except the trivial case of 1. Simmons conjectures that there are no palindromes of the form X^k where k is greater than 4.

"Repunits," numbers consisting entirely of 1's, produce palindromic squares when the number of units is one through nine, but 10 or more units give squares that are not palindromic. It has been erroneously stated that only primes have palindromic cubes, but this is disproved by an infinity of integers, the smallest of which is repunit 111. It is divisible by 3, yet its cube, 1,367,631, is a palindrome. The number 836 is also of special interest. It is the largest three-digit integer whose square, 698,896, is palindromic, and 698,896 is the smallest palindromic square with an even number of digits. (Note also that the number remains palindromic when turned upside down.) Such palindromic squares are extremely rare. The next-largest one with an even number of digits is 637,832,238,736, the square of 798,644.

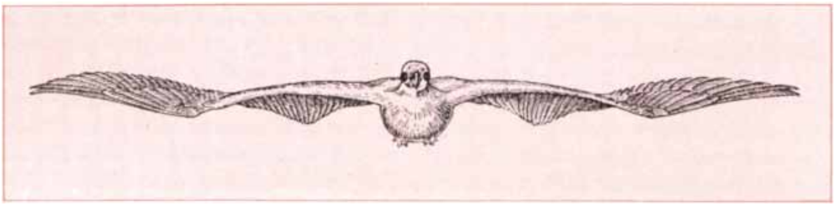
Turning to language palindromes, we first note that there are no common English words of more than seven letters that are palindromic. Examples of seven-letter palindromes are *reviver*, *repaper*, *deified* and *rotator*. The word "radar" (for radio detecting and ranging) is notable because it was coined to symbolize the reflection of radio waves. Dmitri Borgmann, whose files contain thousands of sentence palindromes in all major languages, asserts in his book *Language on Vacation* (Scribner's, 1965) that the largest nonhyphenated word palindrome is *saippuakauppias*, a Finnish word for a soap dealer.

Among proper names in English, according to Borgmann, none is longer than Wassamassaw, a swamp north of Charleston, S.C. Legend has it, he writes, that it is an Indian word meaning "the worst place ever seen." Yreka Bakery has long been in business on West Miner Street in Yreka, Calif. Lon Nol, the current Cambodian premier, has a palindromic name. Revilo P. Oliver, a classics professor at the University of Illinois who was much in the news a few years ago for his activities on behalf of the John Birch Society, has the same first name as his father and grandfather. It was originally devised to make the name palindromic. If there is anyone with a longer palindromic name I do not know of it, although Borgmann suggests such possibilities as Norah Sara Sharon, Edna Lala Lalande, Duane Rollo Renaud and many others.

There are thousands of excellent sentence palindromes in English, a few of which were discussed in an earlier column on word play (SCIENTIFIC AMERICAN, September, 1964). The interested reader will find the best collection in the Borgmann book cited above, together with many fine palindromes in other languages. Composing palindromes at night is one way for an insomniac to pass the dark hours, as Roger Angell so amusingly details in his article "Ainmosni" ("Insomnia" backward) in *The New Yorker* for May 31, 1969. I limit myself to one palindrome that is not well known, yet is remarkable for both its length and naturalness: "Doc note, I dissent. A fast never prevents a fatness. I



Bilateral symmetry, a visual analogue of the palindrome, is seen in a 12th-century Norman mosaic in Palermo



Bilateral symmetry exhibited by a flying seagull

diet on cod." It won a prize for James Michie in a palindrome contest sponsored by the *New Statesman* in England; results were published in the issue for May 5, 1967. Many of the winning palindromes are much longer than Michie's, but, as is usually the case, the longer palindromes are invariably difficult to understand.

Palindromists have employed several clever devices to make the unintelligibility of long palindromes more plausible: presenting them as telegrams, as one side only of a telephone conversation, and so on. Leigh Mercer, a leading British palindromist (he is the inventor of the famous "A man, a plan, a canal—Panama!"), has suggested a way of writing a palindrome as long as one wishes. The sentence has the form, " '————,' sides reversed, is '————.' " The first blank can be any sequence of letters, however long, which is repeated in reverse order in the second blank.

Good palindromes involving the names of U.S. presidents are rare. Borgmann cites the crisp "Taft: fat!" as one of the shortest and best. Richard Nixon's name lends itself to "No 'x' in 'Mr. R. M. Nixon'?" although the sentence is a bit too contrived. A shorter, capitalized version of this palindrome, NO X IN NIXON, is also invertible.

The fact that "God" is "dog" backward has played a role in many sentence palindromes, as well as in orthodox psychoanalysis. In *Freud's Contribution to Psychiatry* A. A. Brill cites a rather farfetched analysis by Carl Jung and others of a patient suffering from a ticlike upward movement of his arms. The analysts decided that the tic had its origin in an unpleasant early visual experience involving dogs. Because of the "dog-god" reversal, and the man's religious convictions, his unconscious had developed the gesture to symbolize a warding off of the evil "dog-god." Edgar Allan Poe's frequent use of the reversal words "dim" and "mid" is pointed out by Humbert Humbert, the narrator of Vladimir Nabokov's novel *Lolita.* In the second canto of *Pale Fire,* in Nabokov's novel of the same title, the poet John Shade speaks of his dead daughter's propensity for word reversals:

. . . She twisted words: pot, top,
Spider, redips. And "powder" was
"red wop."

Such word reversals, as well as sentences that are different sentences when they are spelled backward, are obviously close cousins of palindromes, but the topic is too large to go into here.

Palindrome sentences in which words, not letters, are the units have been a specialty of another British expert on word play, J. A. Lindon. Two splendid examples, from scores that he has composed, are:

"You can cage a swallow, can't you, but you can't swallow a cage, can you?"

"Girl, bathing on Bikini, eyeing boy, finds boy eyeing bikini on bathing girl."

Many attempts have been made to write letter-unit palindrome poems, some quite long, but without exception they are obscure, rhymeless and lacking in other poetic values. Somewhat better poems can be achieved by making each line a separate palindrome rather than the entire poem, or by using the word as the unit. Lindon has written many poems of both types. A third type of palindrome poem, invented by Lindon, employs lines as units. The poem is unchanged when its lines are read forward but taken in reverse order. One is allowed, of course, to punctuate duplicate lines differently. The following example first appeared in Lindon's article "PD Stands for Palindromes" in a London publication, *Competitors' Journal,* for May 7, 1955:

As I was passing near the jail
I met a man, but hurried by.
His face was ghastly, grimly pale.
He had a gun. I wondered why
He had. A gun? I wondered . . . why,
His face was ghastly! *Grimly pale,*
I met a man, but hurried by,
As I was passing near the jail.

This longer one, also by Lindon, is a recent revision of a poem in Borgmann's second book, *Beyond Language* (Scribner's, 1967):

DOPPELGÄNGER

Entering the lonely house with my wife,
I saw him for the first time
Peering furtively from behind a bush—
Blackness that moved,
A shape amid the shadows,
A momentary glimpse of gleaming eyes
Revealed in the ragged moon.
A closer look (he seemed to turn)
might have
Put him to flight forever—
I dared not
(For reasons that I failed to
understand),
Though I knew I should act at once.

I puzzled over it, hiding alone,
Watching the woman as she neared
the gate.
He came, and I saw him crouching
Night after night.
Night after night
He came, and I saw him crouching,
Watching the woman as she neared
the gate.

I puzzled over it, hiding alone—
Though I knew I should act at once,
For reasons that I failed to understand
I dared not
Put him to flight forever.

A closer look (he seemed to turn)
might have
Revealed in the ragged moon
A momentary glimpse of gleaming eyes,
A shape amid the shadows,
Blackness that moved.

Peering furtively from behind a bush,
I saw him, for the first time,
Entering the lonely house with my wife.

Lindon holds the record for the longest word ever worked into a letter-unit palindrome. To understand the palindrome you must know that Beryl has a husband who enjoys running around his yard without any clothes on. Ned has asked him if he does this to annoy his wife. He answers: "Named undenominationally rebel, I rile Beryl? La, no! I tan. I'm, O Ned, nude, man!"

The Diophantine problems presented in this department last month have the following answers.

(1) The problem about the farmer and the animals reduces to the Diophantine equation $11x + 5y = 200$. Applying the method of continued fractions explained

last month, three solutions in positive integers can be found:

Cows	*Pigs*	*Sheep*
5	29	66
10	18	72
15	7	78

(2) L. H. Longley-Cook, in *Fun with Brain Puzzlers* (Fawcett, 1965), Problem 87, solves the rectangle problem as follows. Let x and y be the sides of the large rectangle. The total number of cells it contains is xy. The border, one cell wide, contains $2x + 2y - 4$ cells. Since we are told that the border contains $xy/2$ cells, we can write the equation:

$$xy/2 = 2x + 2y - 4 \, .$$

Double both sides and rearrange the terms:

$$xy - 4x - 4y = -8 \, .$$

Add 16 to each side:

$$xy - 4x - 4y + 16 = 8 \, .$$

The left side can be factored:

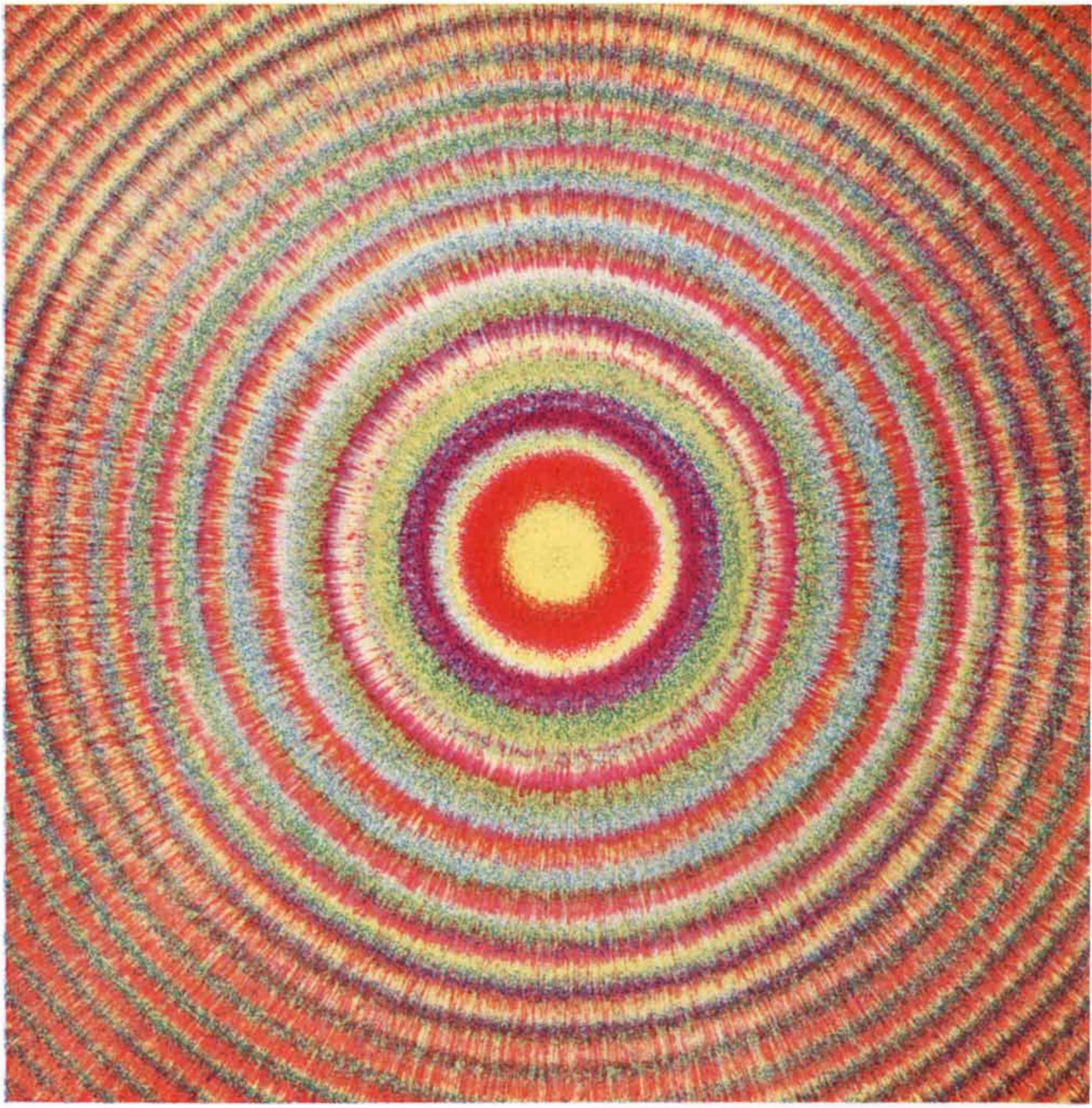
$$(x - 4)(y - 4) = 8 \, .$$

It is clear that $(x - 4)$ and $(x - y)$ must be positive integral factors of 8. The only pairs of such factors are 8, 1 and 4, 2. They provide two solutions: $x = 12$, $y = 5$, and $x = 8$, $y = 6$.

The problem is closely related to integral-sided right triangles. The width of the border is an integer only when the diagonal of the large rectangle cuts it into two such "Pythagorean triangles."

If we generalize the problem to allow nonintegral solutions for borders of any uniform width, keeping only the proviso that the area of the border be equal to the area of the rectangle within it, there is an unusually simple formula for the width of the border. (I am indebted to S. L. Porter of Davis, Calif., for it.) Merely add two adjacent sides of the border, subtract the diagonal of the large rectangle and divide the result by four. This procedure gives the width of the border.

In the answer, given in the May issue, to a question about the moon, the statement that at no time is the moon's path convex should have read "at no time is the path concave." The next sentence made this clear, but the contradiction between the two sentences understandably confused some readers.



THE AMATEUR SCIENTIST

Devices for listening to sounds both in the water and in the solid earth

Conducted by C. L. Stong

Most open bodies of water that cover a few acres or more are filled with animal sounds as diverse and intriguing as those of a deep forest, but the sounds are rarely audible to human ears. A skin diver hears such sounds to a certain extent, but hearing them well calls for a hydrophone: the device that converts underwater vibrations into weak electrical signals. After amplification the signals can be converted into audible sounds by a loudspeaker or a set of earphones or can be recorded on magnetic tape for subsequent reproduction. In this way one can tune in on the staccato clicks of a crayfish, the crunching sound of a rock bass browsing on mussels and the sonorous bellowing of a whale.

The construction and use of two kinds of hydrophone have already been described in this department. One of the instruments is based on a magnetic property of nickel. Vibrations cause the strength of the magnetic field in nickel to vary by periodically stressing the metal. The varying field induces an electric current in a coil of wire that has been wound around the nickel. The currents comprise the signal. The other instrument is based on the piezoelectric property of barium titanate. An alternating voltage appears across opposite sides of this ceramic when it is stressed by acoustic vibrations. The two instruments are described in "The Amateur Scientist" for October, 1960, and March, 1964.

Both kinds of hydrophone work well, but both accentuate sounds of high pitch and require materials that are not readily available to most experimenters. These disadvantages are overcome in an elegantly simple apparatus that has been devised by William A. Watkins of the Woods Hole Oceanographic Institution. He writes:

"The apparatus consists essentially of a coil of wire on a bar magnet that is sandwiched between a pair of iron disks. The strength of the magnetic field is influenced by pressure applied to the disks. Sound vibrations that impinge on the disks vary the pressure periodically. Corresponding variations of the magnetic field generate electrical signals in the coil. In effect variations of pressure alter the reluctance of the magnetic circuit: the circuit's capacity to conduct magnetism. The device is accordingly known as the reluctance hydrophone. Its component parts cost less than $1.

"The details of construction and the techniques of assembly are almost as simple as the device itself. The permanent magnet should be in the form of a short right cylinder. Magnets of this kind are found in small permanent-magnet loudspeakers. I use one about 3/4 inch wide and 1/2 inch long, but these dimensions are not critical. The magnet is made into a spool by fitting the ends with a pair of paper flanges. My flanges were made of stiff paper. Cut two disks 1½ inches wide and perforate the centers by making a series of straight diametric cuts 3/4 inch long. Push the resulting triangular flaps over the ends of the magnet and cement them in place. After the cement has set wind a single thickness of plastic insulating tape over the triangular flaps. The resulting spool is wound with fine insulated magnet wire. I used No. 36 gauge. The strength of the signal increases in proportion to the number of turns. The required amplification varies inversely with the number of turns. A usable signal is developed by 1,000 turns, but I recommend from three to five times that number.

"To apply the winding I attached one end of the magnet to the end of a wooden dowel with rubber cement and chucked the dowel in a hand drill that was supported by a vise. Any similarly improvised winding machine would conserve labor, but the turns can of course be applied by hand. The inner end of the coil was soldered to a short length of No. 18 gauge flexible wire coated with plastic insulation. The soldered joint was insulated with a dab of plastic cement and lashed to the magnet with silk thread. The lead was brought out radially along one flange and tied to the dowel so that it would not interfere with the winding operation. The wire was scramble-wound, that is, wound not regularly as thread comes on a spool but irregularly. The outer end of the completed coil was fitted with a No. 18 gauge flexible lead and was protected by a wrapping of plastic tape.

"The hydrophone and amplifier were connected with a No. 18 gauge, twin-lead rubber-covered cable 50 feet long. One end of the cable was wrapped around the coil and tied. The two conductors were soldered to the leads of the coil and insulated with tape. The weight of the hydrophone is thus supported by the cable without straining the leads. For iron disks I used the covers of electrical junction boxes of the kind designed for house wiring. The tops of tin cans will also work, but thin metal responds preferentially to high-pitched sounds. The sharp edges of the disks should be rounded with a file and smoothed with fine abrasive cloth (or taped) to prevent chafing when the assembly is put into a toy balloon. I use heavy 'Jumbo' balloons, which are available in novelty stores. Stretch the neck of the balloon to admit the disks and then insert the coil. The coil should be located somewhat toward the bottom of the disks when it hangs from the cable; otherwise the disks will be squeezed and pulled away from the magnet when the hydrophone is lowered into deep water. Allow enough air to escape from the balloon so that the assembly will sink in water, then seal the neck of the balloon to the cable with waterproof adhesive tape.

"The hydrophone responds best to frequencies below 500 cycles per second, which is the range of most animal sounds. The output impedance of the coil is on the order of 50 ohms; hence the system is relatively insensitive to stray electrical noise even when it has an unshielded cable hundreds of feet long. The experimenter can vary the device in many ways. For example, its sensitivity and its frequency response can be changed by varying the thickness and size of the iron disks, by supporting the disks away from the magnetic poles by sheets of rubber and by filling the balloon with damping fluid of various kinds. The output is at its maximum at from 10 to 20 cycles per second, and it decreases with frequency to 500 cycles per second (at which point the response is down about 10 decibels). Its response at higher frequencies can be increased by substituting thin iron plates for the junction-box covers and separating them from the magnet by a few thousandths of an inch. The device will then respond to a maximum frequency of about 5,000 cycles, with some loss of sensitivity.

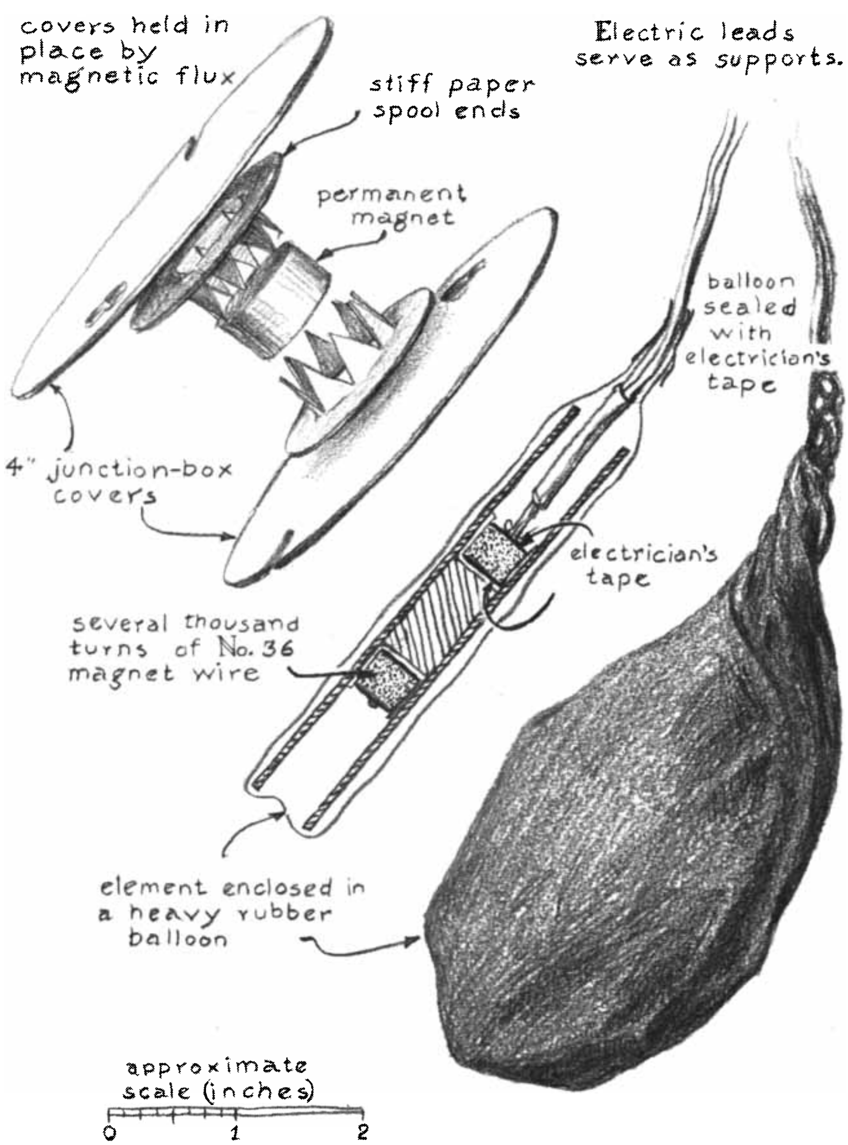
"The required amplification depends on the number of turns in the coil, but it should range from 40 to 65 decibels. Amplifiers of the kind used in most phonographs and tape recorders work satisfactorily. Amplifiers designed for use with crystal pickups and crystal microphones can be matched to the hydrophone by connecting the cable to the 50-ohm input terminals of an impedance-matching transformer and connecting the 100,000-ohm output terminals of the transformer to the input terminals of the amplifier. There will be no extraneous electrical noise if the system is powered by batteries. Some hum may be heard, however, if the amplifier is energized by alternating current. This noise can usually be suppressed by connecting one end of a copper wire to the chassis of the amplifier and trailing a few inches of the other end in the water.

"Not all aquatic animals generate sound, but in recent years marine biologists have discovered scores of species that do so. One would particularly like to know the biological function of such sounds. My own listening has been confined largely to the sounds of sea animals. Porpoises produce clicking noises that seem to be used for echo location. They also emit squeals of various kinds that may serve for communication. The toadfish produces a 'boat whistle' that appears to be related to the establishment and defense of its territory. The seasonal onset of certain sounds made by some fishes suggests an aspect of mating behavior. Shrimp and crayfish emit noisy clicks regardless of what else they may be doing. Amateurs can learn to classify fishes by their sounds as easily as they identify birds by their calls. By keeping careful notes they may also help to solve the riddles of why the sounds are made."

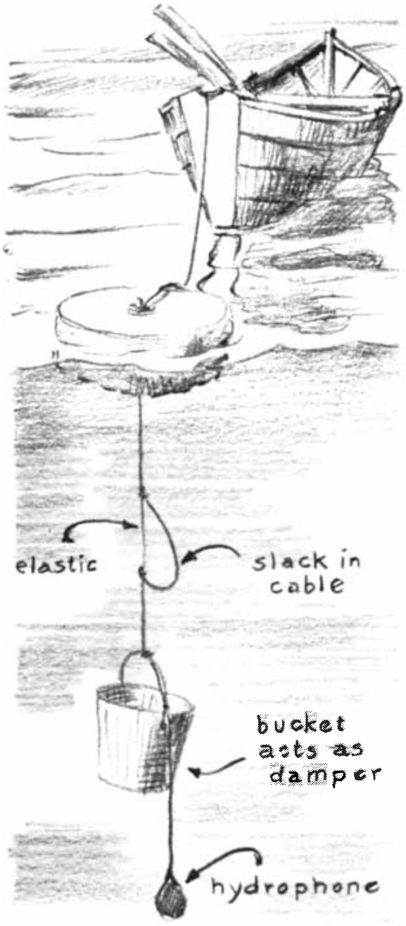
Another kind of sound that is rarely heard is the sound made by the ringing earth. Earth vibrations, which range from about 10 cycles per second to several hours per cycle, are substantially below the minimum frequency to which the human ear responds (about 16 cycles per second). To hear earthquakes and similar disturbances one records seismic vibrations on magnetic tape at the rate of about 3/4 inch of tape per minute and then reproduces the recording at the rate of 7.5 inches per second—a speedup of 600-fold. A number of interesting sounds are heard on typical recordings. The most apparent are two wavering sounds, one slightly above the highest note on the piano and the other close to middle *C*. These sounds are made by microseisms: continuous small tremors of the earth's crust. The seismologist often regards microseisms as noise that limits the useful sensitivity to which he can adjust his instruments. The amateur may find microseisms virtually musical.

The higher of the two tones typically arises from local disturbances: traffic, water running over a dam, waves breaking against a beach and so on. The intensity of the sound tends to increase during daylight hours in heavily populated areas. The note near or below middle *C* appears to arise from a variety of natural causes. Some of the sound has been correlated with cyclonic storms, including barometric "lows," tornadoes and hurricanes. Other contributions have been traced to volcanic activity, the collapse of small natural caves, rock slides and the impact of meteors.

Of more interest are the sounds of earthquakes. Several earthquakes of significant intensity occur somewhere on



A simple hydrophone designed and built by William A. Watkins



A method for suspending the hydrophone

the earth every day. An earthquake of special interest is observed almost every week. On the average one earthquake of devastating proportions occurs each year. Minor earthquakes usually make booming sounds that die out within less than a second. Earthquakes of intermediate intensity resemble distant thunder mixed with short screeches. Big earthquakes may resemble thunder that continues to roll and echo for minutes.

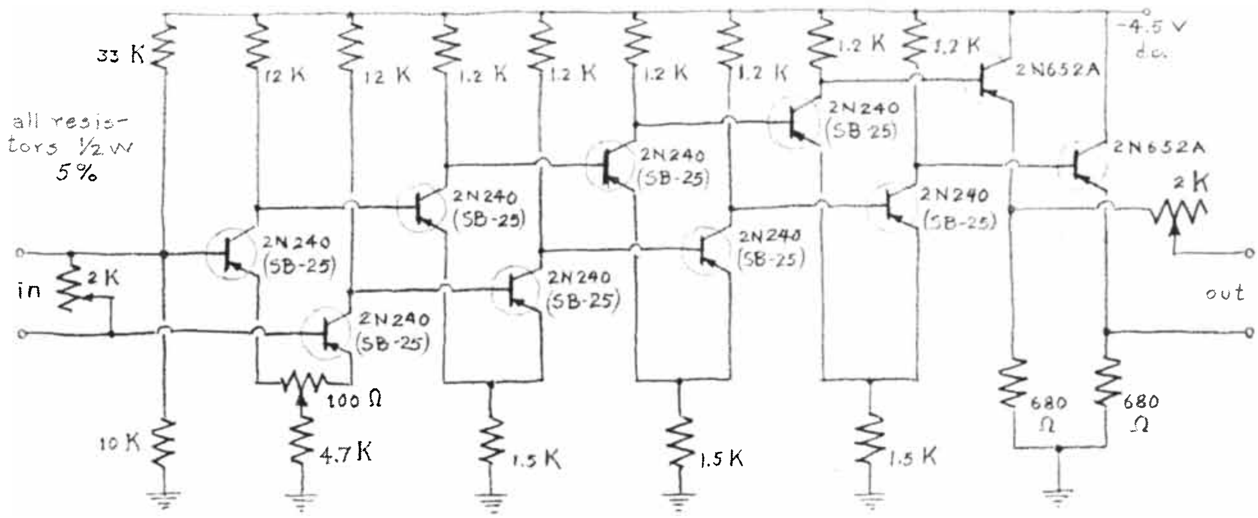
The sound recordings are of little scientific value, either for evaluating the magnitude of a disturbance or for locating the region where an earthquake has occurred. On the other hand, many amateur seismologists record earth vibrations on photosensitive paper or on long rolls of adding-machine tape. The time and trouble of developing the paper or scanning the tape can be conserved by reproducing in a few minutes a sound tape recorded simultaneously during a period of 24 hours or more. Indeed, seismograms can be recorded exclusively on sound tape. Interesting portions can be subsequently transcribed on paper simply by feeding the output of the tape reproducer at an appropriate speed to a pen recorder.

A convenient seismoscope for generating electrical signals that correspond to earth vibrations was developed in 1906 by B. B. Galitzin, a prince of imperial Russia. The device consists of a freely suspended coil of magnet wire, one side of which is located between the poles of a permanent magnet that is anchored to the ground. Earth vibrations displace the magnet with respect to the freely suspended coil. The moving magnetic flux generates electrical signals in the coil. Various ways of suspending the coil have been devised, depending on the plane in which the vibrations occur. To pick up vibrations in the horizontal plane the coil can be supported at the outer end of a structure resembling a garden gate that swings on low-friction hinges. This arrangement is essentially a pendulum that swings in the horizontal plane at a natural period determined by the mass of the bob and the inclination of the upright support to which the hinges are attached. The more the gate "sags," the faster it swings.

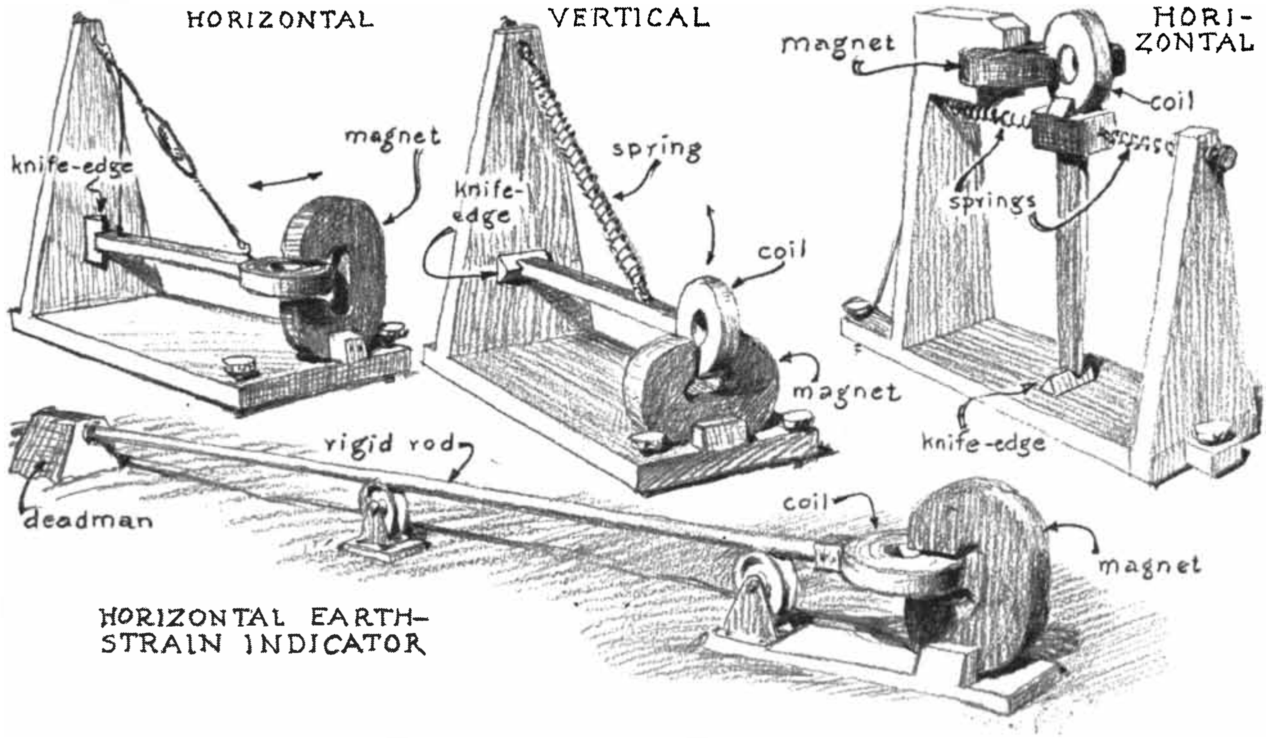
The apparatus is most sensitive to seismic disturbances that correspond in frequency to the natural period of the pendulum. Most seismographs are tuned to a period of 10 seconds, which corresponds in general to the period of the most interesting earthquake waves. The pendulum can also be mounted in the horizontal plane and hinged so that it vibrates in the vertical plane. In this arrangement the weight of the coil and the lever arm on which it is mounted are supported by a spring. The signal is generated by the vertical excursions of the magnet. Less popular are seismographs that employ inverted pendulums. The coil is supported at the upper end of a lever arm that rests on a pivot at the lower end. The pendulum is kept from falling over by springs that exert balancing forces on the four sides of the bob.

Still another arrangement substitutes a long rod for the pendulum. One end of the rod is anchored to the ground; the other end carries the coil. One side of the coil is immersed in the field of a permanent magnet that is supported by a distant pier also anchored to the ground. Seismic waves alter the distance between the piers and so displace the coil with respect to the magnetic field. The weight of the rod is supported by rollers on top of intermediate piers. Schematic representations of the four seismoscopes are shown in the accompanying illustration [*top of page 120*]. Construction details have been presented in this department (April, 1952, and June, 1953).

The amplitude of the relative motion



Schematic circuit of a seismograph amplifier made by Bruce Knudtson

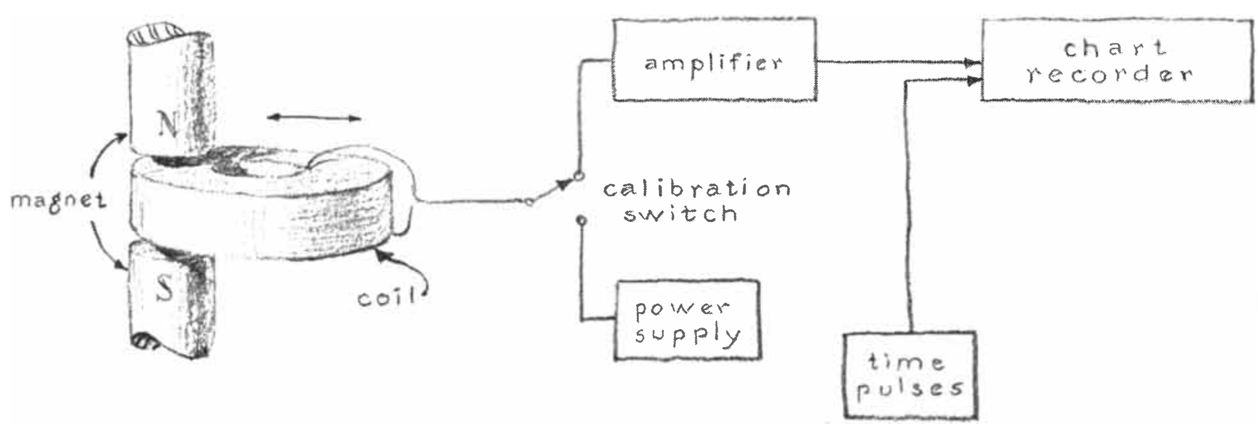


Various arrangements of the Galitzin seismoscope

between the magnet and the coil depends on the magnitude of the earthquake and the distance of the instrument from the center of the disturbance. Surface oscillations of more than 20 feet can occur above the center of a violent earthquake. Waves that spread outward from the center can cause the surface to vibrate more than an inch in 20 seconds at a distance of 1,000 miles. In contrast, the amplitude of microseisms, as they are normally recorded in most U.S. localities, is on the order of millionths of an inch. Although the amplitude of microseisms is small, they generate an adequate signal in a coil of 50,000 turns in a magnetic field of 3,000 gauss.

An inexpensive amplifier that increases the energy of the signal sufficiently to operate a magnetic tape recorder, a pen recorder or both simultaneously has been constructed by Bruce Knudtson of Burbank, Calif. "My amplifier," writes Knudtson, "is of the differential type. It responds to frequencies that range from direct current to 10,000 cycles per second, and it increases the signal voltage by a factor of approximately 200. The circuit employs 10 inexpensive transistors of two kinds, 16 half-watt resistors and three potentiometers [*see bottom illustration on page 118*]. The amplifier operates from, and is stabilized by, a regulated power supply of 4.5 volts. The voltage-regulator portion of the circuit includes a Zener diode that maintains a constant reference voltage, a potentiometer for adjusting the output potential, and a pair of transistors that maintain the output at constant potential even though the input may vary from five to 20 volts. The components of both the amplifier and the voltage regulator are mounted on prepunched panels of plastic. The amplifier is housed in a grounded aluminum case to minimize electrical interference.

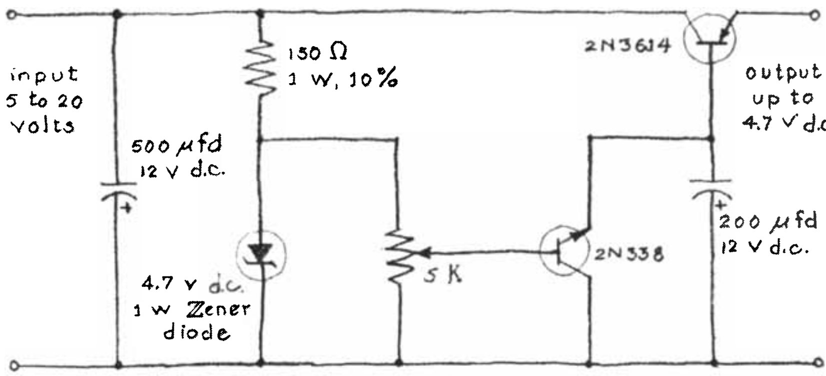
"The amplifier has three adjustments. A 2,000-ohm potentiometer across the input terminals provides a load on the coil. The load dissipates energy that



Schematic circuit of Knudtson's voltage regulator would otherwise tend to sustain oscillations when the coil is set in motion. It is adjusted to bring the coil to rest as it makes three oscillations. The second adjustment, provided by a 100-ohm potentiometer, controls the relative gain in the two branches of the amplifier circuit. It is set at the point where no voltage appears across the output terminals in the absence of an input signal. The third potentiometer controls the gain of the amplifier.

"In addition to the seismoscope, the amplifier and the recorders, the system includes two other essential components: an auxiliary power supply and a device for generating accurately timed pulses of current. The power supply, which can be a single dry cell, is used for setting the pendulum in free oscillation during the initial adjustment of the instrument. Power is momentarily applied to the coil by a double-pole, double-throw switch. The pulse of current causes the coil to swing from its equilibrium position, after which it vibrates at its natural period. The rate of vibration is registered by the pen recorder. It can then be adjusted both by altering the inclination of the pendulum suspension and by adding mass to the pendulum arm. The total mass of my pendulum is six kilograms. The period is 10 seconds. The load connected across the input of the amplifier is adjusted to the point where the pendulum comes to rest after three oscillations.

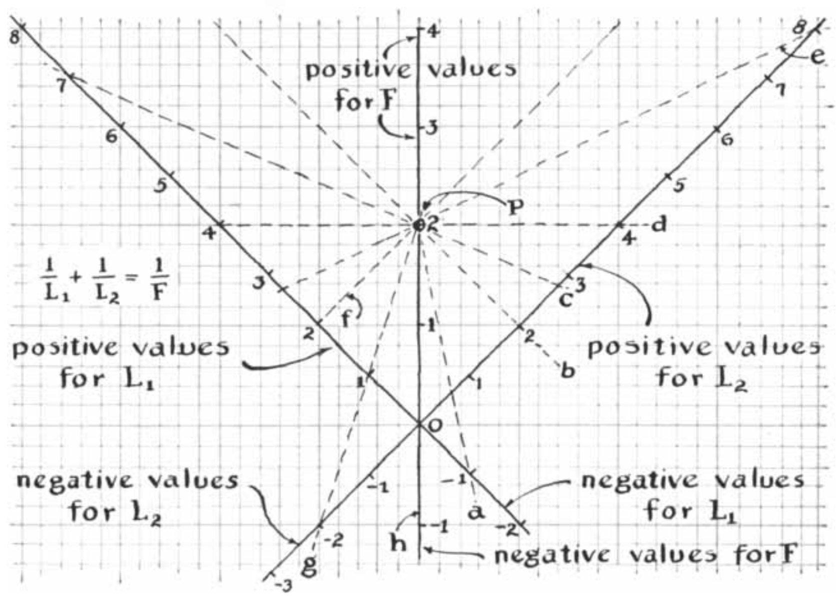
"The interpretation of seismograms requires an accurate time reference. Conventionally time signals and seismic disturbances are recorded simultaneously. The time intervals should be generated by an accurate clock that is checked regularly against time signals broadcast by the National Bureau of Standards. An electromagnetic relay associated with the clock can be arranged to momentarily close a circuit at regular intervals, such as once per minute. The pulses can either actuate a second pen of the chart recorder or cause the recording pen to register a series of uniformly spaced peaks on the graph (or clicks on the sound tape). Incidentally, the sound tapes can be erased and used many times, a feature of considerable interest to the amateur who must operate on a limited budget."



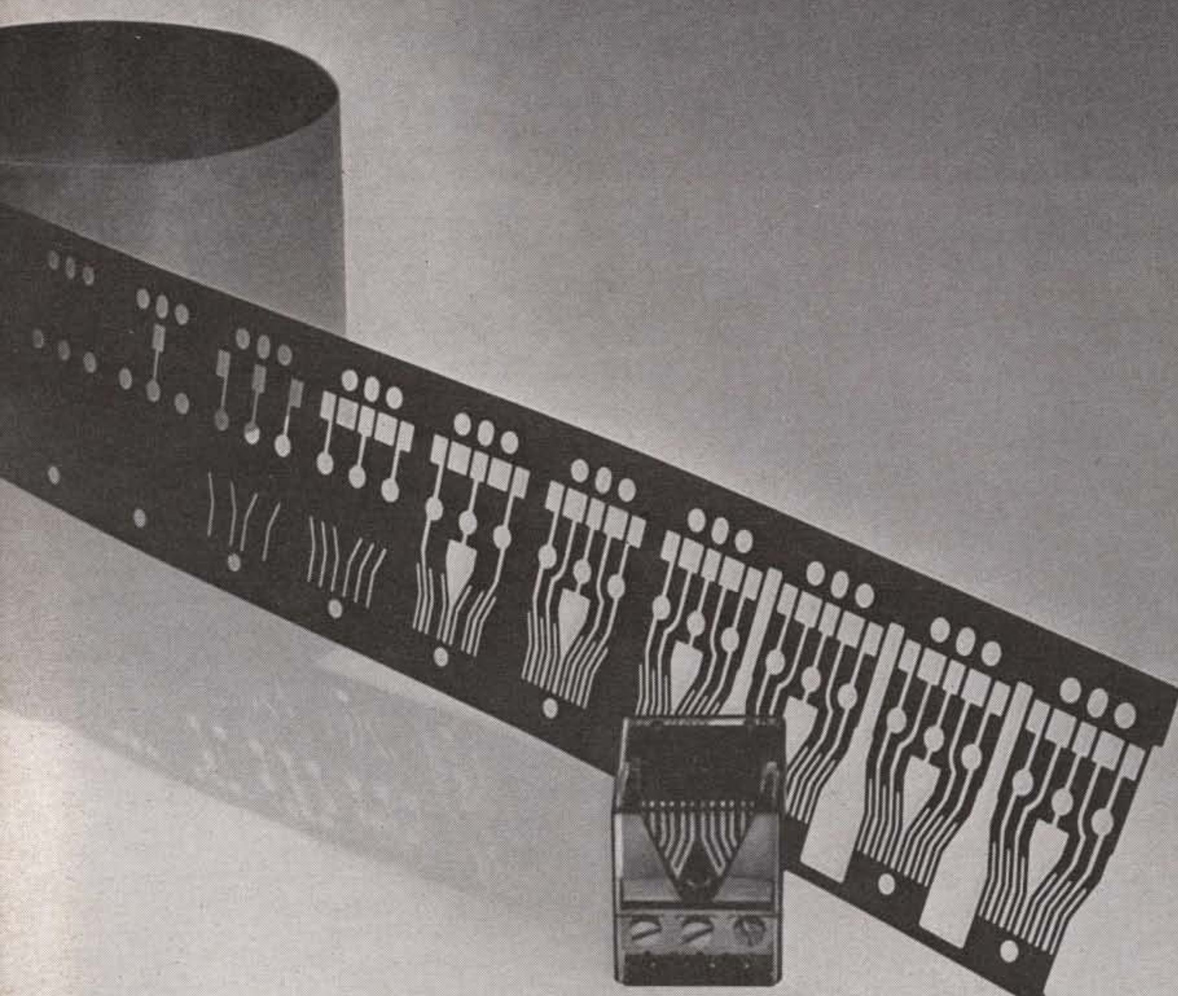
Schematic circuit of Knudtson's seismograph

Roger Hayward, who illustrates this department, frequently turns for diversion to optical experimentation. His "hobbery," as he calls it, is filled with instruments of his own devising, from simple magnifiers and a traveling microscope to a precision spectrograph that operates well into the range of ultraviolet radiation. Like everyone who does optical experiments, Hayward has frequent occasion to determine the distance at which an object must be placed from a lens of known focal length so that its image will come to focus at a specified distance on the other side of the lens. The three lengths are linked by a simple arithmetical relation: the sum of the reciprocals of the object and image distances equals the reciprocal of the focal length of the lens. In symbolic terms, $1/L_1 + 1/L_2 = 1/F$, where L_1 is the object distance, L_2 is the image distance and F is the focal length of the lens.

"Solving this equation repeatedly by hand," writes Hayward, "can become rather tedious business when one is attempting to improvise an apparatus by the technique of cut-and-try. Much time and trouble would be spared if one knew the approximate answer in advance. Being rather a lazy fellow by nature, I recently amused myself by devising a nomogram for solving the problem graphically [*see bottom illustration on this page*]. The known focal lengths of lenses are plotted on the vertical coordinate of the nomogram. Positive values appear above the origin (*O*) and negative values below. Corresponding object distances and image distances are plotted on adjacent scales at 45 degrees, as shown in the illustration. A straight line drawn through the point that represents the focal length of any positive or negative lens connects the conjugate foci, as if represented by the dotted lines of the nomogram. Precision is not expected of any nomogram. On the other hand, graphic solutions do indicate how the parameters change with respect to one another, and they enable the experimenter to select with minimum effort a lens that will do the job. One then finds the exact solution by doing the number work."



Roger Hayward's nomogram for the lens formula



A new age for bronze

Commercial metals consist of crystals whose properties, such as yield strength, may be greater in one direction than another. Because normal casting and forming tend to orient the crystals in a preferred alignment, metals often acquire directional properties or "texture."

Bell Laboratories scientists have been studying the laws that govern crystal alignment. By applying a computer technique called linear programming to a model of crystal deformation they can predict the result of metal-forming operations and, hence, the properties of the end material. This indicates that texture can be controlled to produce stronger materials.

A practical result of these studies is the development, by Gilbert Chin, Robert Hart, and Bud Wonsiewicz, of an improved high-strength phosphor bronze. (This copper/tin mixture, known since about 3500 BC, was probably man's first alloy.) Formed into springs for relays, connectors, and other devices, the improved alloy should give greatly increased life, savings in material, and new opportunities for miniaturization. (Photo shows a miniature relay and the steps in stamping relay springs from a sheet of the new bronze.)

Relay springs are continually flexed, so the bronze must have high yield strength (force needed to permanently deform a sample of given area). Up to a certain force, the crystal —and hence the bulk metal—is elastic. Beyond that, there is slip or shear along crystallographic planes: the metal bends permanently.

To strengthen the bronze, the Bell Labs scientists prescribed severe rolling to develop texture. A 97% reduction in thickness increased the metal's yield strength to 1½ times the value attained in usual commercial practice, where 70% is the maximum reduction. As the computerized model predicted, greatest yield strength was transverse to the direction of rolling.

Moreover, the additional rolling enhanced particle precipitation in the crystal matrix. Hence, heat treatment after the extensive rolling increased the yield strength of the bronze an additional 40%. The material became more resistant to slip or strain. This cannot be achieved with less heavily worked material.

Tests at Bell Laboratories indicate dramatic increases in the life of these important components of telephone systems. And Western Electric, manufacturing and supply unit of the Bell System, has used the new alloy in pilot runs of miniature relays.

For the Bell System, such improvements in basic materials mean better service in communications.

From the Research and Development Unit of the Bell System:

Bell Labs

BOOKS

The history of technology, the velocity of light and the investigation of sleep

by Philip Morrison

THE MUSES AT WORK: ARTS, CRAFTS, AND PROFESSIONS IN ANCIENT GREECE AND ROME, edited by Carl Roebuck. The M.I.T. Press ($12.50). AGRICULTURAL IMPLEMENTS OF THE ROMAN WORLD, by K. D. White. Cambridge University Press ($15). CHINA AT WORK, by Rudolf P. Hommel. The M.I.T. Press ($10). MOVING THE OBELISKS, by Bern Dibner. The M.I.T. Press ($1.95). We can know the past by the hand of both clerk and craftsman: the author leaves his symbolic record, the artisan the work of his bench. Neither alone is adequate. The ancient writers usually did not themselves practice the artisan's trade, nor did they know it deeply; some of their remarks are mere metaphors or allusions. They make schoolboy errors or omit key details (such as hidden means of fastening and early stages of preparation), even when they were eyewitnesses. Often the work does not survive; all the ships of Rome that we know are wrecks, mere traces on the bottom. There are other routes to the past. Artists can help, with their representational symbolism and their lines on paper or stone giving a visual account of old ways of work. There are written records that were never meant as conscious descriptions, such as contracts and account books, often detailed but sporadic and full of enigmatic costs and counts. Finally there is the experiment of reliving the past, of working again in the old way. Sometimes it is a fully conscious scientific experiment, such as the rediscovery of the means of making the red- and black-figured Attic vases: the same red clay was used in the vase body and in preparing the glaze; its iron oxide impurities gave the color contrast under a controlled sequence of oxidizing and reducing steps in firing. (Professor Roebuck's book gives the black glaze recipe in modern form, with a pinch of Calgon!) Sometimes the past is relived in the daily work of the traditional rural craftsmen, particularly in lands such as Iran and China between the world wars. Here the erratic overlay of new ideas is what blurs the old blueprint.

These four volumes, each at a different level of density and readership, span the methods of the history of technology. The topics they examine hold our interest. The working muses of Professor Roebuck's happy title are those of building, sculpture in bronze and in stone, pottery, farming, sailing, trading, music making and acting. Each is invoked in one broad survey chapter by an expert classicist, mostly from the texts but with exciting examples, with plenty to add to the software. The chapters derive from a series of public lectures; they are well aimed at a general readership, with the footnotes postponed to the back of the book, no long snippets of untranslated text, a lively and personal tone of address and a handsome book design. (Text and photographs both come out rather too gray in tone, at least in the review copy.)

Lionel Casson of New York University has an absorbing and expert chapter on ships. The Mediterranean, he shows us, was cut by keel only during the summer. At that season "calms are a frequent plague." Warships had to maneuver or fail; they used a breeze of oars. The ancient galley was "an overgrown racing shell . . . light enough . . . to be run up on a beach or into a ship by its crew." The ram evolved in the ninth century B.C.; the warship was now a self-propelled bronze-shod missile. Fifty oarsmen pulled away, one to an oar. More power meant more men, and the beam of the ship could not be much extended. The result was the trireme, with three banks of oarsmen.

The trireme had 170 skilled rowers; these men practiced for long hours, in order to be, in the Greek phrase, "beaten together." They had simulators ashore—wooden platforms for rowing practice. Ramming was subtle: you had to impact at just the right speed. If you were too slow, the enemy could back away; if you were too fast, the ram was embedded too deeply to be pulled out, and you risked being boarded.

In Homer's day the warriors who landed from the ships were themselves rowers. By trireme times the oarsmen were citizens of the poorer classes. They owned no weapons or armor, but they could learn to row. In spite of all data to the contrary out of Hollywood and Cinécitta, there were no galley slaves in the ancient world. The imperial Roman navy was powered by young men from the provinces. They signed up for a 26-year hitch as professionals, and they looked to retirement with the status of Roman citizen. There is even a letter on papyrus from a young Egyptian boot assigned around A.D. 150 to the fleet at Misenum, enclosing a picture—alas, it is lost to us—that "unquestionably showed him in his new sailor suit."

Classical farming is also illuminated by a chapter in the Roebuck book. *Agricultural Implements of the Roman World,* however, is a monograph intended for scholars, illustrating one by one each kind of spade, hoe, sickle and fork, with an account of its nature and use and a collection of all important references in surviving texts. What demands notice is an account of the Roman reaping machine. Pliny devotes three lines to it. Palladius describes a different type in one brief detailed passage. Then in 1958 there was found in southern Belgium a low-relief stone panel, part of a large funerary monument, that, with three long-known but much less recognizable representations, makes us sure that useful machines existed. They were devised and used on the large latifundia in the level wheatlands of old Gaul from the Marne to the Moselle. The lighter version was a shallow wheeled frame pushed by a mule to bring a set of blades against the heads of the grain, which were torn off into an open box. The height was smoothly varied by an operator walking behind and adjusting his weight against the shafts. The machine paid off in prosperous Gaul, where harvest labor was short. It was not matched until the Beverley reaper of the 1850's, a rather similar machine.

The last two books are reprints of outstanding older books. The Hommel book was first published in 1937 by the Mercer Museum of 18th-century tools in Doylestown, Pa. It was Henry Chapman Mercer who planned and financed the expedition to China. The book records what Hommel saw while roaming through central China during the 1920's, when the country was broken into fitfully warring provinces. "The task ... was to record by photographs and descriptions the tools and implements of the Chinese people." That task is brilliantly accomplished, in spite of "the innate aversion of the people to the camera" and to the taking of measurements with a rule. Hommel measured many items surreptitiously, using secret marks on his cane. Knowing little Chinese, he always worked with translators, and the book shows no contact with the vast literature in Chinese. It is all craftsmen and no clerk, although Hommel did know and use the Western historians. It is a unique work, a truly touching monument to the time and the place, and an endless fascination of strange and clever methods: men marking lines, making bean curd, mending cast iron by a portable means of remelting, drilling with hand drill the eye in needles made of iron wire, dipping candles and carrying loads on the cutaway bamboo bearing pole. It is a world of handwork, and it is the ocean from which leap the flying fish of modern Chinese earth satellites. There are more than 500 photographs and an excellent index.

The fourth work is a devoted and learned story, deliciously illustrated, of the huge Egyptian obelisks, burdens of a couple of hundred tons, that were brought to Rome by the half-dozen and are also found in Paris, London and New York. Here we have the apotheosis of the rigger, extending across all ages. The high point of the book is the moving of the obelisk in the Piazza of St. Peter, planned, computed, modeled and carried out in 1585 and 1586 by a prince among engineers, Domenico Fontana. His book reports it all, with marvelous baroque engravings. (Some are reproduced on gatefolds in this edition, which is a bargain for the prints alone.) What a scene in the great square: a plain filled with hard hats, each man to his capstan or his rope! There were 900 men, 74 horses and a web of ropes extending in all directions of the compass. Police enforced strict silence (under penalties including death) so that orders could be heard when they were sounded by trumpet and bell. "One of the prettiest legends in engineering history" came from that dramatic silence. At a critical moment the ropes stretched and "an old Genoese sailor ... called out *'Acque alle Funi!'*—Water on the ropes!" Saved! Alas, it is only folklore. It may have happened like that in Constantinople once.

Note the publishers of these books. The older Cambridge is justly well known for its works in the history of science and technology; the newer one by the Charles River Basin now has a most attractive list of such books, both originals and reprints such as *Moving the Obelisks,* heretofore found only under the imprint of the private library of the author.

THE VELOCITY OF LIGHT AND RADIO WAVES, by K. D. Froome and L. Essen. Academic Press ($5). Light travels in free space at the ultimate speed. To fix that speed accurately in relation to our man-made units is plainly a goal the measuring physicist cannot resist. Even before Einstein measurement of the speed of light had yielded fundamental insights: exactly that speed enters as the needed dimensional constant when one compares the electrostatic charge on a carefully measured pair of condenser plates with the current the same arrangement gives off when it is discharged through a magnetic galvanometer. The result, first found in 1857, lay within a percent or two of the direct value that was obtained by direct measurement on the earth's surface (and long before by astronomers). The entire structure was built into the electromagnetic theory of light by James Clerk Maxwell and his successors. By the first decade of this century Einstein had given c (as it is always denoted) its sovereignty over all other speeds.

This brief, attractively written book is a complete overview of men's concern with c. It presents a succinct account of the history of the effort and an up-to-date summary of the standards of length and of time that must enter. Up to 1940 the classical means (such as A. A. Michelson's mile-long evacuated pipe, which was of doubtful utility) are merely sketched and the results are tabulated. The modern period begins with the postwar world. Indeed, it was exactly the development of microwave technology for radar that began the new era of precision for this fundamental quantity.

The key to the modern approach is the role of radio-frequency measurements. Electrical waves of constant form and frequency can be generated by quartz crystals, say, and used to trigger faster "slave" oscillators. Sums and differences can be found easily by the use of the bag of electronic tricks. All measurements can be related to standard clocks, of whatever style is current. It was Dr. Essen himself, working at the National Physical Laboratory just after the war, who first used the method of measuring the dimensions and the resonance frequency of a sharply resonant microwave cavity. Essentially (no pun intended) he found the distance between the repeated reflections of the microwave from the cavity walls. The transit time was given with great precision by the usual frequency techniques indispensable to the radio laboratory. "The enormous improvement obtained by using modern radio frequency techniques is evidenced by the fact that an experiment carried out quickly almost as a side-line to the main programme of work should give a precision of measurement at least 50 times as great as that given by years of painstaking effort with the classical optical method." After one good try the error was cut to about one kilometer per second, out of the 300,000 kilometers per second that is c. The main error sources were the length measurement and the role of tarnish on the silver cavity wall.

Microwaves remain the basis of the best measurements so far. They present radiations with wavelengths short enough so that man-made equipment can still easily contain many wavelengths (radio-broadcast waves are 1,000 feet long), and yet with frequencies low enough for us to count the cycles of the wave against an accurate clock. Optical vibrations are still too fast for us to count. The other author, Dr. Froome, holds the present accuracy record. He used a large microwave interferometer, counting about 1,000 "fringes" of his invisible four-millimeter radiation, working in a large wind-tunnel room. The dominant sources of error in this 1958 work, which was good to a third of a part per million, were the measurement of length down the cast-iron machine-tool bed Froome used and the uncertainty in correcting for the effect of the air in the room.

A quite different path was marked out by the needs of precision surveyors. Using either a light beam or a microwave beam to measure distance has sparked a revolution in geodetic work. First in Sweden and then in South Africa successful instruments have been made and sold worldwide by the thousands.

They work on a similar principle, whether with light or microwaves. The carrier beam is chopped electrically tens of millions of times per second. It is sent out and back, by passive reflection or by active echoing. The phase of the signal and of the echo are compared, which fixes the distance to within an inch or better, a small fraction of the chopping wavelength. The ambiguity of just which cycle is being received is removed step by step by the standard trick of changing the wavelength a little and repeating. The entire process has been engineered into a robust routine. Nowadays trilateration—measuring three sides of a triangle 10 or 20 kilometers long—has replaced the older triangulation from one carefully taped base line. The work is far faster and is more accurate.

In the course of these geodetic developments the value of *c* had to be fixed. The surveys of several nations, motivated by their own interests, led to some splendid standard base lines. The results obtained rival the best laboratory values of their time (a decade ago) except for the atmospheric uncertainties. An error of a part per million is introduced into a light beam by a change in air temperature of one degree Celsius or by a change in pressure of a few millimeters of mercury. With a base line of several miles it is hard to be that sure of the air. The very best base lines—there is one nearly a kilometer long in Finland—are now patiently measured by optical interferometric means with quartz-spaced mirrors and white-light fringes that neatly solve the ambiguity problem.

What lies ahead? Lasers will carry us the next step of the unending way to exactness. At the Joint Institute for Laboratory Astrophysics in Boulder, Colo., they expect a result in a year or so that is accurate to a few meters per second. The length is struck off in a 30-meter evacuated pipe. (The optical wavelength makes smallish equipment usable.) The length can be calibrated directly with the meter-defining standard wavelength from the krypton atom. The trick is that by using laser purity and intensity two light frequencies can be made to beat against each other. The beat frequency is then slow enough to be counted electronically. The fringes can be counted for both light waves (actually they are infrared), and the answer is calculated to high accuracy.

This is somehow a topic no one caught up in physics ever fails to love; here it is well presented, at a not very exacting mathematical level, by two men who have themselves pioneered in it. You can safely bet that c is 299,792.5 ± .1 kilometers per second.

SLEEP: PHYSIOLOGY AND PATHOLOGY, edited by Anthony Kales. J. B. Lippincott Company ($14). PSYCHOTOMIMETIC DRUGS, edited by Daniel H. Efron. Raven Press ($15.95). "Dreaming is not a capricious, fleeting, psychic anomaly, but rather one aspect of a basic biological function universally distributed among all mammals." Many of us have watched a dog twitching as he slept and have imputed to him a doggy dream. The experts, armed with polygraph recording, do a little better. They paste electrodes on the scalp or place them deeper, noting from several channels the tenths-of-a-millivolt signals, running in frequency from fractioned cycles to a few tens of cycles. The signals are an objective, if tortuous and narrow, path to the mind of another creature, be it dog, cat, opossum, donkey or man. Normal, healthy men may sleep only three hours per day—two authenticated cases are at hand—or up to 10 hours. A donkey spends only three or four hours sleeping per day, a rabbit 14. Since the 1953 work of Eugene Aserinsky and Nathaniel Kleitman (Dr. Kleitman himself is an emeritus participant but a lively one in the first of these two Los Angeles symposia) the polygraph has made clear that sleep is "comprised of two alternating ... states. Far from suggesting rest ..., the second of these exhibits the qualities of intense organismic excitation." In "paradoxical," or rapid-eye-movement (REM), sleep, which begins every hour or two and lasts from a few minutes to half an hour, a human sleeper shows a deeply relaxed muscle tone and low-amplitude but mixed-frequency brain waves, with the rapid synchronous movements of the two eyes "scanning" under closed lids that give REM sleep its name. All mammals show REM sleep, but frogs and birds do not. Arousal from REM sleep usually brings the vivid report of dreams, even from people who maintain they have never had a dream in their life. The congenitally blind, by some accounts, show no REM. It is held that during REM sleep "insignificant signals are ignored but important ones" awaken. The frightening nightmare and its elaborate recall occur out of REM sleep. The classical incubus—the sleeper waking fearful and oppressed in breath but without the content of a dream to recall—comes out of the deep sleep of "Stage 4."

The symposium has a pedagogical aim; there was a large audience of physicians, whose questions are practical and who mainly seek therapeutic judgments. Most drugs that are commonly used for sleep therapy tend to reduce REM sleep, with unknown consequences, good or bad. Cats deprived of REM sleep are strange and hypersexual; humans deprived of it, but not over such long periods, are at least excitable. The issue is unclear.

Frederick Snyder of the National Institute of Mental Health presents a biological scheme for understanding the odd, many-roomed mansion of sleep the direct-current amplifier has given us. He conjectures that REM sleep is a sentinel period, a periodic state of inward arousal first needed by the defenselessly sleeping early mammal that roamed the cold night among the torpid reptiles, rulers of the warm sunlit hours. It is also plain that the more sleep, the less need for food. The sleepless and timid ruminants eat a great deal, but the direction of cause and effect is unclear. Telemetry of the polygraph signal should soon tell us how sleep operates in the full pulse of life outside the laboratory. Human subjects asleep in their own beds have already been studied by telemetry linked all night to a recorder by way of the home telephone line.

Men kept awake for a solid week (one 17-year-old for 11 days) sometimes, but not always, display a "model psychosis": visions, panic, feelings of persecution (rather well founded, it might appear). The key to mental illness is not as close at hand.

The second symposium—a small, intense, argumentative, technical one, full of critical discussion and no little rudeness—is after the same trophy. Do the powerful drugs of jungle peoples or of the Swiss pharmaceutical laboratories provide a bottled model for mental disease? The secondary question is whether we can understand their effects, and the tertiary one bears on their increasing public use. The answer is complex and partial; the mind's construction is perhaps less concealed in the bizarre subtleties of the drug taker's behavior than in the wiggly signals taken from a sleeper's eye muscles, but it is still illegible. The drugs are powerful. LSD produces nothing closely typical of the schizophrenic; LSD hallucinations are mainly visual, and the true disease is a multimedium performance. D-amphetamine comes closer. "Another patient, while watching television, turned off the set ... and sat up in bed.... A 'giant oscillator' in the ceiling was sending rays which controlled his thoughts.... 'I know this is part of the experiment ... but I should have been told.' " Four out of four volunteers sustained such an acute paranoid psychosis. That took a few days and a half-gram of the drug. A dose of mescaline induced complete blindness in the left eye of one graduate-student experimenter; the blindness passed in a few minutes "but it gave us a healthy respect for what such a drug could do." One of the synthetic cannabinols induced a strange state: "I preferred to be left alone.... There was never any stimulus or inclination for increasing activity.... Even the most bland and unappetizing food was very delightful."

This tangled tale is full of hints, with some nonsense and some insight. The philosophical understanding many of these research men display seems inadequate to their needs. Reality is richer and more constraining than the consensus some of them take as its definition. Much the most profound comment came from a man who sees not drug-users but epileptics and other patients with gross physical lesions of the brain. For some of the other workers Newton seems to be mechanism, all right, but not Boltzmann. On the other hand, the group and the papers exhibit all levels, and modern gas chromatography and structural chemistry get more play than solipsism. It is a spicy stew.

One cannot conceal a feeling of dismay about some of these human experiments. The surgeon has long recognized the irony that his knife cuts as well as heals. The research psychiatrist, with his case history and his private research ward and his ethically unpaid informed volunteers "who had previously self-administered large doses" ought very soberly to assay the value of his tabular results. It is tempting to bang a newly repaired radio set to see if the soldering is tight, but the circuitry of the mind is not yet even in the manuals.

THE CURIOUS HISTORY OF THE GOLF BALL: MANKIND'S MOST FASCINATING SPHERE, by John Stuart Martin. Foreword by Chick Evans. Horizon Press ($6.95). In good King James's glorious days the Scots were granted a monopoly on the manufacture of "featheries" (goose down tightly stuffed into a shrunken horsehide cover), and such balls were the *sine qua non* of golf until the Victorian "guttie" (solid-molded from a dried Malaysian tree gum called gutta-percha). The price dropped fivefold; the sport grew. From Goodrich in Akron in about 1900 came the modern ball, machine-spun from rubber thread under tension. It is tripartite, with a small solid core (sometimes liquid-filled), mainly present as a necessity of practical winding-machine design, and an outer hard cover, first of gutta-percha and later of other natural rubbery plastics. Mass production ensued, and the familiar chain of technical progress began, leading to aerodynamic dimple design, routine tension tests, X-ray centering inspection and automatic driving machines for quality control. Real innovation in golf balls is not yet dead. A New Jersey inventor, James Bartsch, the hero of this droll, hyperbolic work, developed and in 1967 patented a new homogeneous molded ball, of a specifically developed synthetic polymer (based on polybutadiene) covered with a polyurethane hide. Guttie simplicity is back, but in our era of molecular design. The solid polymer took a tenth of the U.S. market overnight; today its shortcomings—real and imputed (it does shatter alarmingly)—seem to limit its acceptance.

THE SMOAKE OF LONDON, TWO PROPHECIES. FUMIFUGIUM: OR THE INCONVENIENCE OF THE AER AND SMOAKE OF LONDON DISSIPATED, by John Evelyn, and THE DOOM OF LONDON, by Robert Barr. Selected by James P. Lodge, Jr. Maxwell Reprint Company, Elmsford, New York ($5). John Evelyn, as candid as ever, petitioned Charles II in 1661 with a scheme "to meliorate and refine the Aer of London" from "that Hellish and dismall Cloud of SEA-COALE" which rises not, he held, "from the *Culinary* fires . . . but from some few particular Tunnells and Issues, belonging only to *Brewers, Diers, Lime-burners, Salt,* and *Sope-boylers,* and some other private Trades." He proposed that "all those *Works* be removed five or six miles" downriver, and that the fields between be planted with hedgerows of sweet-smelling trees. Well, the King didn't act.

In *The Doom of London,* a slight turn-of-the-century short story, the Canadian author describes the time when a seven-day calm and a seven-day fog came together, so that Londoners died wholesale and only the narrator, saved by an oxygen source left for a trial at his place of work, survived with a few stragglers. The entire grim, somewhat formal tale is a plausible prevision by 50 years of what actually happened in the great London smog of 1952.

Poor "old *Par,* who lived in health to an Hundred and fifty years of Age, was not so much concerned with the change of Diet (as some have affirmed) as with that of the *Aer,* which plainly withered him, and spoyled his Digestion in a short time after his arrival at *London.*" The Evelyn piece is a mine of timely citations.

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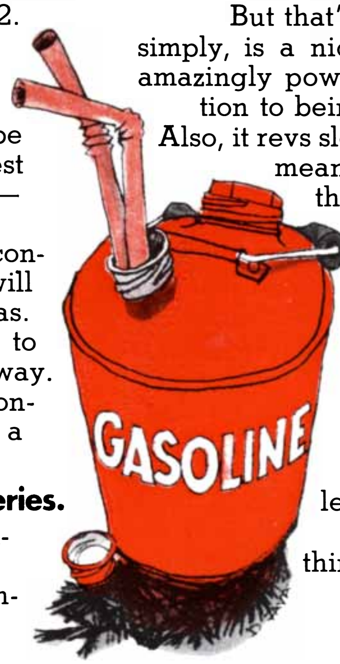

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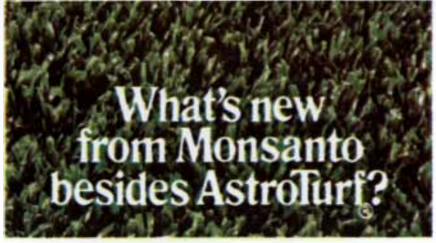

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