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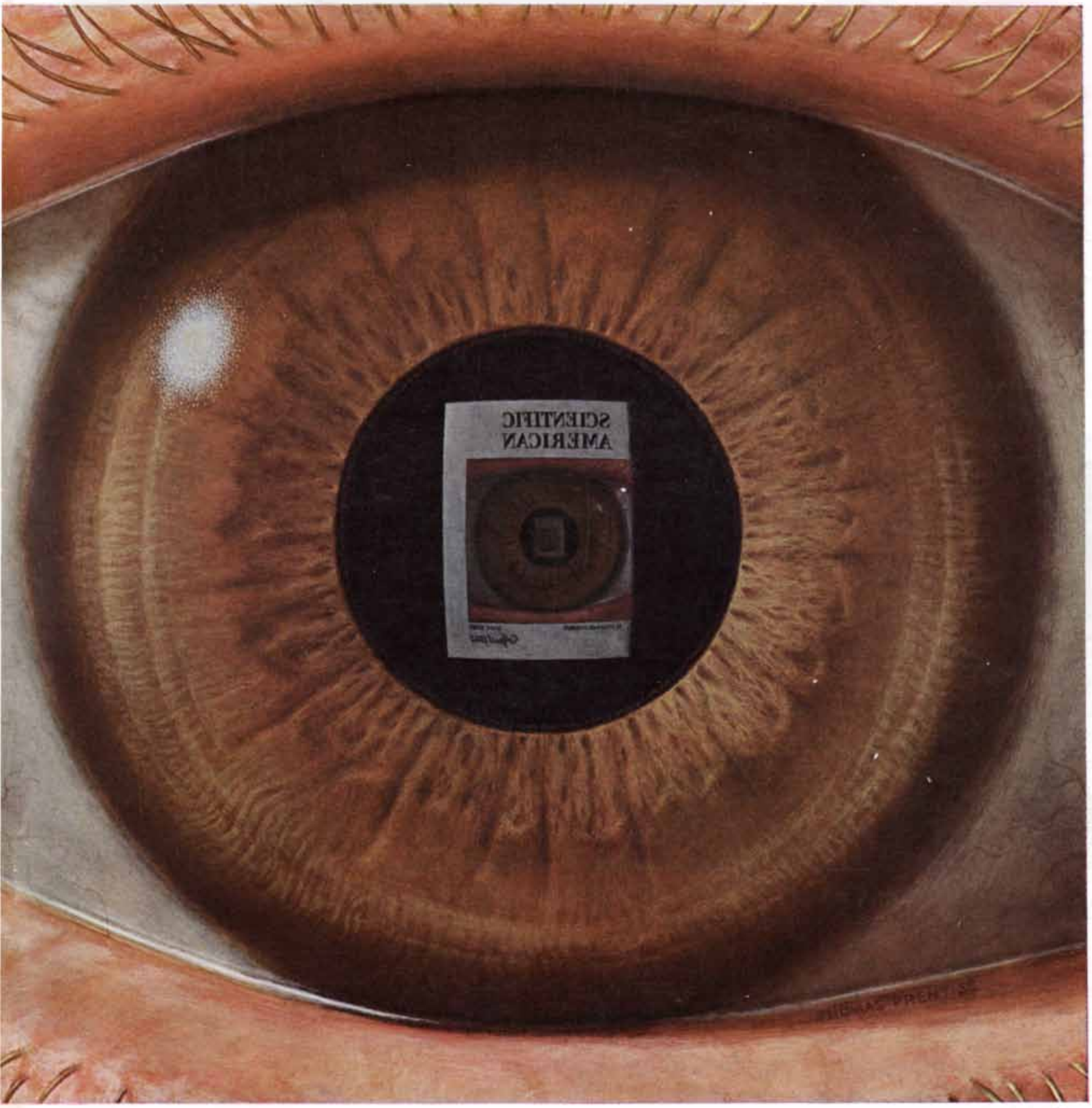

ATTITUDE AND PUPIL SIZE

SIXTY CENTS

April 1965

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A normally friendly environment can be decidedly hostile under certain conditions. Through M&T chemistry, there are defenses against a number of such situations.

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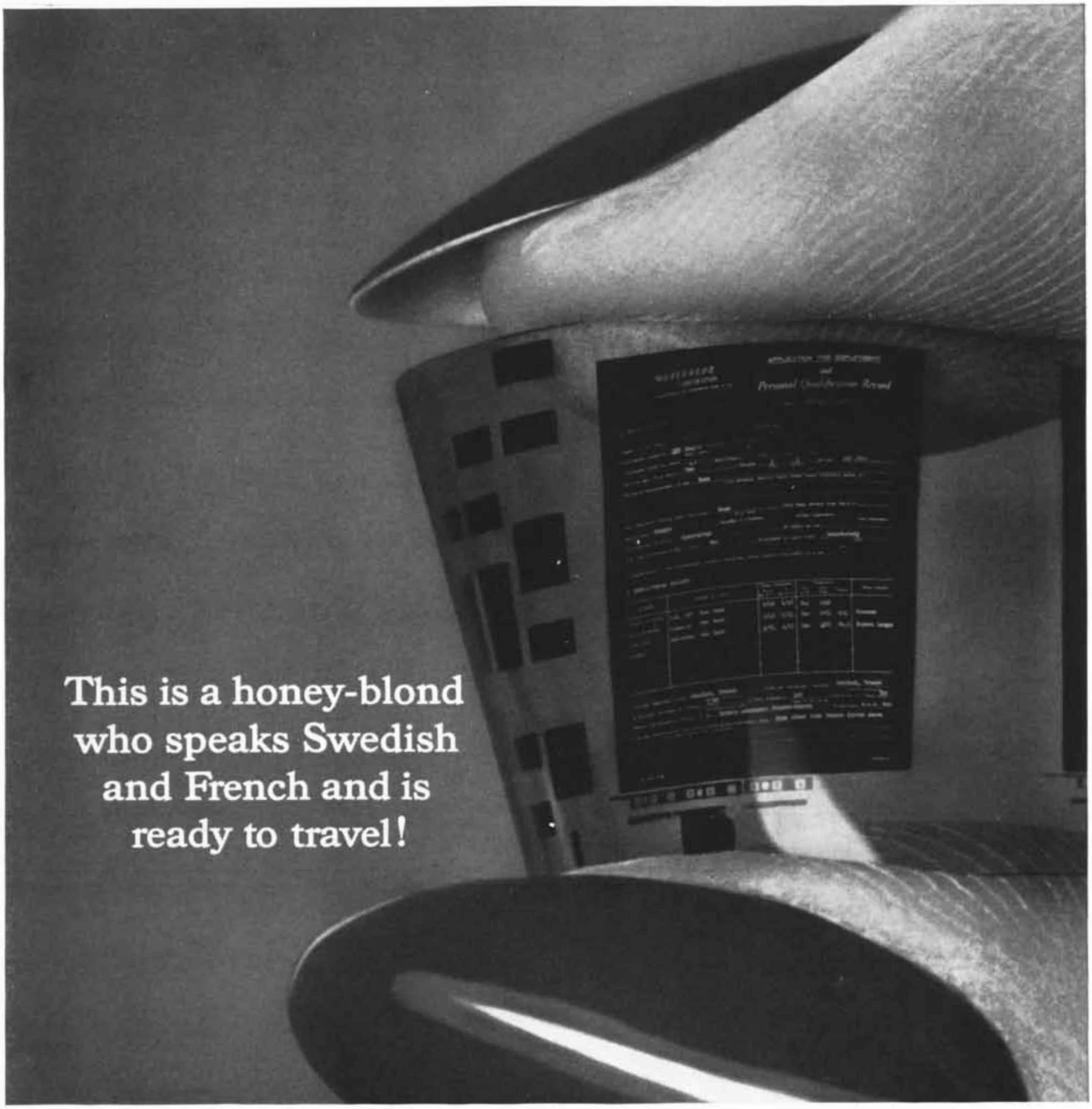
This is a honey-blond who speaks Swedish and French and is ready to travel!

Established 1845 SCIENTIFIC AMERICAN April 1965 Volume 212 Number 4

ARTICLES

DEPARTMENTS

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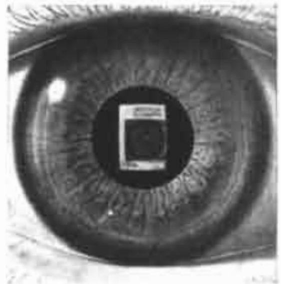

THE COVER

The painting on the cover shows the pupil of the human eye, which contracts and dilates not only in response to changes in the level of illumination but also in response to changes in attitude (see "Attitude and Pupil Size," page 46). In studying the effects of attitude Eckhard H. Hess and his colleagues at the University of Chicago present their subjects with a variety of pictures, ranging from "pinups" to Presidential campaign photographs. Within the pupil in the painting is a reflection of what the reader sees in viewing the cover of this month's Scientific American, namely the cover of this month's Scientific American. It is perhaps needless to add that the cover reappears smaller and smaller in infinite regress.

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Cover painting by Thomas Prentiss

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LETTERS

Sirs:

I am writing to protest John E. Ullmann's intemperate and emotional attack on Eugene P. Wigner, and his equally emotional reaction to the idea of civil defense ["Letters," SCIENTIFIC AMERICAN, February]. I grant Professor Ullmann the right to his distaste for civil defense; I do not believe this gives him the right to justify this distaste by invoking spurious technical arguments.

For example, Professor Ullmann claims to have calculated that a plausible civil defense system for the U.S. would cost $\$200 \times 10^9$; the recently issued Harbor Study on Civil Defense, under the auspices of the National Academy of Sciences, places the figure at around $250 per person for blast shelters. Professor Ullmann implies that blast shelters are necessary for every member of the population; common sense suggests that, just as in World War II shelters were provided only for the big city targets, so blast shelters would be needed only for the population in target areas. Professor Ullmann implies that our current fiscal policies, in which 8 percent of the gross national product goes into defense, have brought the nation to the verge of wrack and ruin; he surely knows that our country enjoys a higher level of prosperity than ever before in its history.

But I do not wish to belabor Professor Ullmann's misstatement of fact and distortion of the technical situation. I urge only that all of us, scientists and nonscientists alike, heed seriously what Professor Wigner, one of the world's foremost, most honored and most responsible scientists, says: Civil defense cannot be brushed off flippantly. It behooves all of us to examine the facts seriously and studiously before allowing our emotional distaste for the situation in which we find ourselves to determine our course of action.

ALVIN M. WEINBERG

Director
Oak Ridge National Laboratory
Oak Ridge, Tenn.

Sirs:

In August and September, 1963, along with 60 others, I took part in a National Academy of Sciences study of civil defense and its relation to the entire U.S. defense program. The study, called Project Harbor, was directed by Professor Eugene P. Wigner of Princeton. On the basis of the Harbor work and further study since, I disagree with several statements by Professor Ullmann concerning Wigner's reply to Jerome B. Wiesner and Herbert F. York ["National Security and the Nuclear-Test Ban"; SCIENTIFIC AMERICAN, October, 1964].

Professor Ullmann implies that passive defense is impossible because of a presumed "overkill" ability by the Russians (the ability to destroy all lives and property in the U.S. many times). He ignores statements by responsible officials (e.g., Secretary of Defense Robert S. McNamara to the Democratic Platform Committee on August 17, 1964) that refute this contention. The actual Soviet strategic offensive power is reported to be a small fraction of ours. I do not mean to suggest that this power could not at present cause widespread destruction in the U.S. but only that the effects are finite and do *not* represent overkill.

As a consequence of great offensive superiority, there would seem to be two fruitful courses open to the Government. First, the Department of Defense could, by a reallocation rather than an increase in defense spending, increase the investment in systems to limit damage to the U.S. in the event of a war.

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Such a war could occur, for example, either accidentally or as the result of irrational behavior by a leader of any one of the growing number of nuclear-armed countries. One such damage-limiting system is civil defense. Second, the Government could increase its efforts to achieve a workable arms-control program. The recent announcement of the end of the Minuteman construction program (*Missiles and Rockets,* January 4) is consistent with both courses of action.

Professor Ullmann's reference to "overkill" may also be taken to mean that a continued effort to greatly extend the U.S. offensive superiority is not warranted. With this position I would agree. Wigner's letter also advocates an increase in our damage-limiting capabilities, principally in civil defense, rather than an increase in our offensive power.

Of course the cost of various damage-limiting programs is an important variable in evaluating their effectiveness. National fallout protection (a component of one possible civil defense system) has been generally accepted as the least expensive and, for many situations, a most effective program (National Defense Message from the President, January 19). Other systems, such as those containing blast protection for major metropolitan areas, need to be evaluated and compared. In this connection Professor Ullmann's estimates of \$250–\$300 billion for national blast protection, presented to the Hébert Armed Services Subcommittee on June 21, 1963, are not substantiated by other engineering estimates (e.g., the Project Harbor Summary Report).

I agree with Professor Ullmann that military, economic and political strength all contribute to the security of our country. In my opinion, discussions of the arms problem such as the one begun by Wiesner and York and continued by Wigner are also important for the country's security. Scientists who take part in serious, conscientious analysis and criticism of the country's defense policies should not be dismissed as members of some fictitious "arms-scientist establishment" with opinions from "cloud-cuckoo-land."

J. C. BRESEE

Oak Ridge, Tenn.

Sirs:

My critics term "emotional" the technical objections contained in my letter. If emotions are not to be called on in choosing the form of our society and the quality of our lives, then an "emotion-free" choice speedily becomes a dehumanized one. My critics' stridency on this point, moreover, is symptomatic of a growing dismay at the technical dead end of the arms race to which so many able men have linked their professional competence.

My shelter-cost estimates are substantiated in my article in *No Place To Hide* (Grove Press, 1962). The summary report of Project Harbor is not a technical rejoinder to my findings that a blast-shelter system would cost at least \$200 billion.

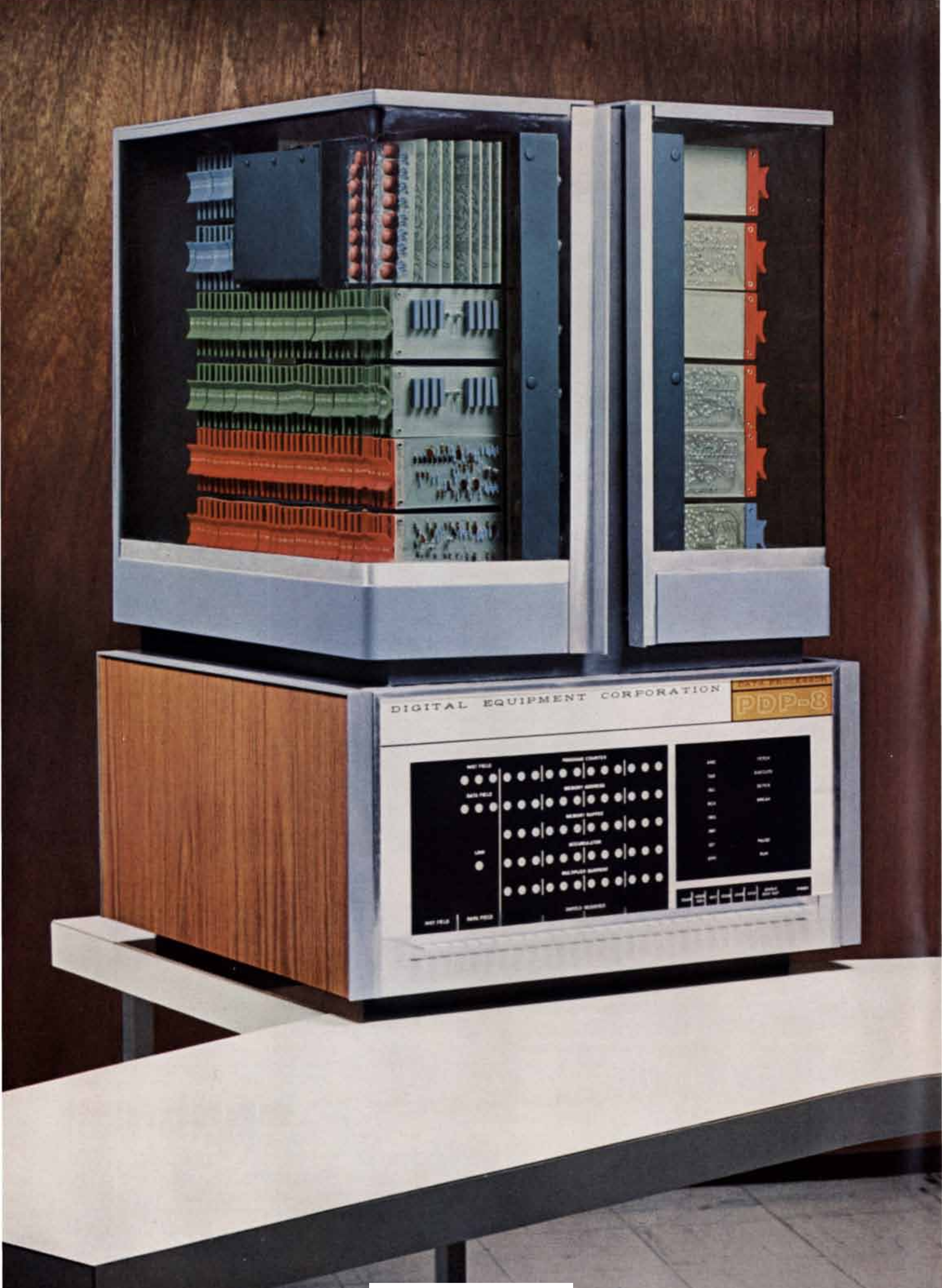
The "establishment of the arms scientists" is no fiction. When I wrote my letter, I was unaware of Professor Wigner's professional involvement as a civil defense consultant. Whenever civil defense and related subjects are formally discussed in Washington, there is a long procession of directly interested scientists and others claiming independent judgment (cf. my analysis of civil defense witnesses in *The Correspondent,* November–December, 1963). Criticism is essential to the integrity of science and no scholarly distinction can confer immunity from it, particularly where special pleading is involved.

JOHN E. ULLMANN

Professor and Chairman
Management, Marketing and
Business Statistics
Hofstra University
Hempstead, N.Y.

ERRATUM

In "Science and the Citizen" for February it was indicated that a neutrino observatory was nearing completion in Idaho under the direction of John N. Bahcall of the California Institute of Technology. Actually the observatory is under the supervision of Raymond Davis, Jr., of the Brookhaven National Laboratory and Don S. Harmer of the Georgia Institute of Technology and is supported by the Atomic Energy Commission. Bahcall made the theoretical calculations on which the design of the neutrino detector was based. The observatory will be located in the Homestake Gold Mine in South Dakota and will be completed next year.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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

APRIL, 1915: "Until recently it had been assumed that a given chemical element must always possess the same atomic weight. The inclusion of the radioactive elements in the periodic system, effected by Kasimir Fajans and also by Frederick Soddy about a year ago, shows that we must assume the existence of elements which vary as much as eight units in atomic weight, with corresponding variations in their radioactive properties but without any change in their chemical behavior. In reviewing the subject *Umschau* observes that this conception was based on indirectly proved, or inferred, properties of the short-lived radioactive elements. Hence it was important to prove by direct experiment that two elements that appear chemically identical may have different atomic weights. The way to such an experimental demonstration was pointed out by Fajans, who concluded that the atomic weight of the lead formed in uranium ores in the course of millions of years as the final product of the disintegration of uranium probably differs from the atomic weight of lead extracted from common lead ores. This conclusion has now been confirmed experimentally by very careful determinations of the atomic weights of specimens of lead of diverse origins. The research was suggested by Fajans and was carried out by his former assistant, Lembert, in the laboratory of Prof. T. W. Richards at Harvard University, which is celebrated for its accurate methods of determining atomic weights. The atomic weight of lead obtained from uranium ores was found to be 206.6, whereas ordinary lead gave the distinctly different value of 207.1."

"So many disappointments have been recorded following announcements of new methods of making rubber synthetically that rubber importers and users are now exceedingly wary in accepting statements to that effect. But news has just come from Baku, Russia, which seems valuable enough to deserve a thorough test in the California oil fields. It seems that there are certain fractions in the Baku crude oil (which are also prevalent in the California oil) boiling between 98 and 106 degrees which yield nearly 20 per cent of their weight in adipic acid. This adipic acid can be converted into butadiene through the action of its own amide in a commercially practicable process. Butadiene, again, can be converted into caoutchouc by means of another simple and inexpensive process. Experiments are already under way to determine the practical value of this discovery."

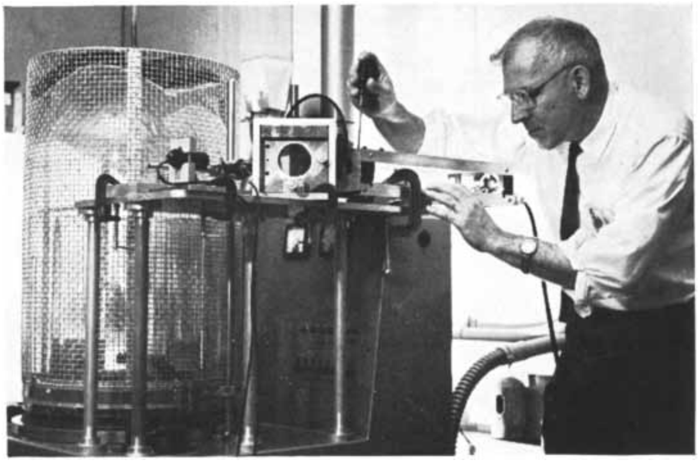
"According to a recent estimate of the U.S. Public Health Service the number of persons in this country who are victims of the drug habit is about 70,000 and the number of doses of narcotic drugs consumed by them annually is about 850,000,000. This estimate is based on figures collected in the state of Tennessee, where under a recently enacted anti-narcotic law 1,403 permits were issued in six months to persons petitioning for the privilege of using narcotic drugs, and the consumption of such drugs amounted to 8,498,200 average doses."

Scientific American.

APRIL, 1865: "Never since the beginning of the world has there been so widespread, exalted and profound joy as that which filled the hearts of the American people when the telegraph flashed the intelligence over the land that the central power of the rebellion was broken in pieces. And well we might rejoice. This great event stirred all the emotions of the heart. The first thought was a feeling of triumph over a formidable enemy that was struggling to destroy the nation, an enemy defiant, haughty, contemptuous and absolutely fiendish in his malignant cruelty. But the strongest emotion was gratitude for the safety of the unity and power of the nation through the great peril. It was well understood that the question at issue was whether this country should be broken up into hostile and contending fragments, burdened with the support of vast armies and navies, passing the time in brief alternations from peace to war, now watching with jealousy the growth of each other's power and now cutting each other's throats; or whether we should be one great, united, harmonious people, settling our disputes by decisions of the Supreme Court, with

Report from

BELL LABORATORIES



D. L. Perry, who developed techniques for making high-reflectivity mirrors at Bell Laboratories, adjusts laser used for measuring thickness of dielectrics. The laser beam is split, and one part of the beam is compared with another part reflected from a monitor slide. High signal-to-noise ratio of laser system permits accurate measurement of quarter wavelength of layers.

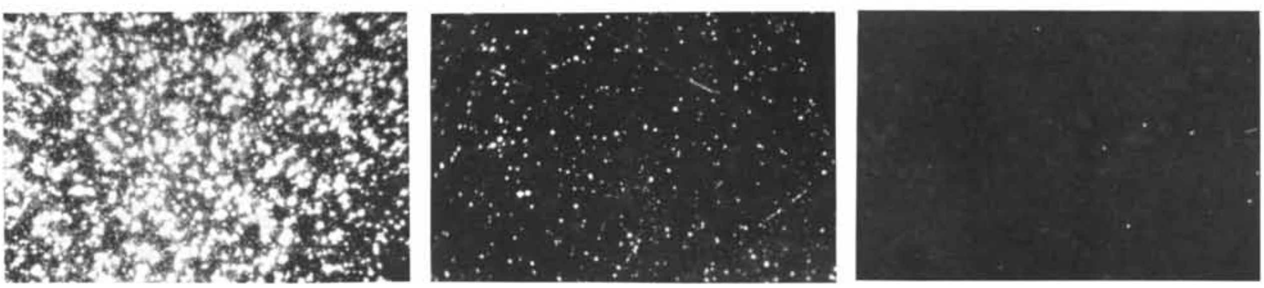
New techniques for making nearly perfect mirrors

Even the best mirrors scatter and absorb some of the light incident upon them. Because the power output of a laser depends importantly on this loss of light at mirrors, scientists at Bell Laboratories have sought to push the reflectivity of mirrors as nearly as possible to 100%. Preliminary measurements indicate that reflectivities of over 99.8% can be achieved at a given wavelength and that broad-band mirrors are also possible spanning the visible spectrum (4200 to 7400 Angstroms) with reflectivities greater than 99.5% for all wavelengths in the band.

The best mirrors are made by applying many layers of dielectric material of precisely controlled thickness to the mirror surface. In the past the number of such layers has been limited to about 15. One reason is that "large" (order of a wavelength of light) particles accumulate in the layers; these act as scattering centers, so that additional layers decrease rather than increase the reflectivity.

At Bell Laboratories a method has been developed to apply 27 or more layers successfully, with consequent increase in reflectivity. This method involves strict attention to the cleanliness of the substrate, careful control of evaporation temperature at a point just below the melting point of the dielectric material, and precise measurement of layer thickness. The thickness measurements are performed using a continuously operating gas laser. One of the most significant findings was that some dielectrics, when used in a powder form, were causing the large particles to appear in the layers. Apparently entrapped gases within the powders were suddenly released on heating, causing small showers of particles to be projected into the layer—a difficulty corrected by using a properly prepared "chunk" form of the material.

Bell Telephone Laboratories
Research and Development Unit of the Bell System



Microscope photos showing about 2½mm² each of three mirror surfaces. Oblique lighting causes each scattering particle to appear as a spot of light. The photos compare a poor mirror (left), an average mirror with 15 dielectric layers which, in addition to scattering loss, will have a few tenths of a percent transmission loss (center), and a mirror with 27 layers made at Bell Laboratories with refined coating technique (right). The additional layers plus a nearly total absence of large particles result in a greatly increased reflectivity.

the inconceivable blessings of popular education spread throughout our borders, with an organized, prosperous, contented industry, with the means of happiness more abundantly and more widely diffused and with the masses of the people raised higher on the scale of humanity than has ever yet been known in the history of the human race. For the right determination of this great debate the heart of the nation is moved with inexpressible gratitude to the brave and devoted soldiers of our patriot army. With this gratitude to the soldiers comes the slow but inevitable recognition of the greatness of their commander. The surrender of Lee is a fitting conclusion of the masterly generalship of General Grant and the splendid fighting of his noble army."

"An appalling and overwhelming calamity has befallen the nation. The Chief Magistrate has been stricken down by the hand of an assassin; and, as one man, the people are aghast at the magnitude of their loss. In the flood tide of victory, in the fullness of the joy which our successes in overthrowing the rebellion warranted, a pall drops upon the flag, ashes are strewn upon the laurel, the jubilant shouts are changed to cries of mourning. It is too early to foresee the political results of this awful crime. Our hearts are sick unto death at the sudden revulsion which has taken place in public affairs. Though the hand of justice may not close over the offender presently, the execrations of all right-minded men will forever settle upon the infamous cause of it. The deep grief which sits upon the faces of the people shows how dear to them was the simple, honest, upright man who so lately guided us. Wise in judgment, inflexible in decision, magnanimous to his enemies, pure in private as in public life, history will record no brighter name upon its pages than that of Abraham Lincoln."

"Captain James Anderson of the Cunard mail steamer *China* has been appointed to command the *Great Eastern* during the laying of the Atlantic telegraph cable. The *Great Eastern* will sail from Valencia, Ireland, about the 1st of July and may be expected at Heart's Content, Newfoundland, by the middle of that month. There were 1,662 nautical miles of cable completed on the 21st of March, and the whole 2,300 miles will be made and on board the *Great Eastern* in May. It is confidently expected that Europe and America will be in telegraphic communication before the 20th of July."

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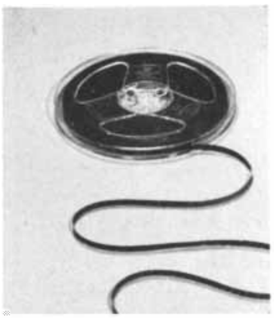

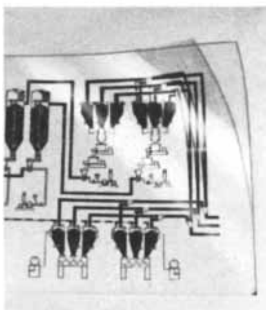

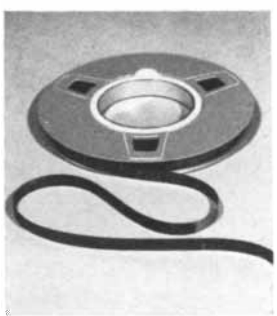

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THE AUTHORS

WASSILY W. LEONTIEF ("The Structure of the U.S. Economy"), Henry Lee Professor of Economics at Harvard University, is in residence at the Center for Advanced Study in the Behavioral Sciences in Stanford, Calif., during the current academic year. A native of Russia, he came to the U.S. in 1931 after study in Europe and two years as economic adviser to the Chinese government. During World War II he was a consultant to the U.S. Department of Labor, where he applied his "input-output" system of economic analysis to the problems that would be created by the shift from a wartime economy to a peacetime economy. He has also served the United Nations as a consultant on the economic impact of disarmament and on the economic development of newly independent nations.

JEAN-PIERRE CHANGEUX ("The Control of Biochemical Reactions") is *maître-assistant* in biochemistry at the University of Paris. He describes his post as "something more than an assistant but less than a professor." Changeux also does research at the Pasteur Institute, where in 1959 he began an investigation of the mechanism by which the activity of enzymes is regulated. That work has led him into other investigations of cellular regulatory processes in an effort to elucidate the mechanisms by which a metabolite, or regulatory signal, controls a chemical reaction at the molecular level. Before he went to work at the Pasteur Institute, Changeux did research in marine zoology.

ECKHARD H. HESS ("Attitude and Pupil Size") is professor of psychology and chairman of the department of psychology at the University of Chicago. A native of Germany, he came to the U.S. to study at Blue Ridge College and did graduate work in physiological psychology at Johns Hopkins University before going to Chicago in 1948. In addition to his work at Chicago, which is primarily in perception, Hess spends much time at an experimental station in Maryland, where he studies the "imprinting" of ducks and geese and also seeks to devise ways of fending off raccoons that prey on the birds.

HENRY H. KOLM and ARTHUR J. FREEMAN ("Intense Magnetic Fields") are respectively a founding member and associate director of the National Magnet Laboratory at the Massachusetts Institute of Technology. Kolm is a native of Vienna who came to the U.S. in 1939, served in military intelligence during World War II and then obtained undergraduate and graduate degrees at M.I.T. Subsequently he joined the university's Lincoln Laboratory and did work that led eventually to his affiliation with the National Magnet Laboratory. In addition to his professional activities he is interested in the problems of instrument flight and air traffic control and holds a commercial pilot's license. Freeman, a native of Poland, came to the U.S. in 1937, obtained undergraduate and graduate degrees at M.I.T. and then taught at Brandeis and Northeastern universities before joining the National Magnet Laboratory in 1962. He played a major role in the development of the record-breaking 255,000-gauss magnet recently announced by the laboratory.

ROBERT J. RODDEN ("An Early Neolithic Village in Greece") is field director of a Cambridge-Harvard archaeological expedition at the site he describes in his article. A native of Washington, D.C., he is a candidate for a doctoral degree from the University of Cambridge, where he went after doing undergraduate and graduate work at Harvard University. He writes that his expedition's work at Nea Nikomedeia, the site in Greece, promises to provide "for the first time in the Aegean area an environmental framework in which to place Europe's first farming groups." He also describes an "archaeological experiment" involving "the construction of a house, using the materials and the building techniques most probably employed by the early Neolithic settlers at Nea Nikomedeia; this summer the structure will be burned down and then excavated, so that the results can be compared with the archaeological evidence obtained from original dwellings."

KENNETH D. ROEDER ("Moths and Ultrasound") is professor of physiology at Tufts University, where he has served since 1931. He was born in England, was graduated from the University of Cambridge and did graduate work there and at the University of Toronto. "My lifelong interest in insects," he writes, "probably stems from a childhood enthusiasm for butterfly collecting." Roeder's research deals mainly with the biological aspects of insect behavior. In addition he is "an

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incurable tinkerer with mechanical and electronic gadgets," an activity that "led at one time to the construction of an electromechanical analogue of certain phases of cockroach behavior and has played a part in the work on moth hearing." He says he has "always felt that if one can make a subject clear and interesting to a nonspecialist, it becomes clearer and more interesting to oneself."

ROBERT S. RICHARDSON ("The Discovery of Icarus") has begun a career as a free-lance writer after 33 years as an astronomer and writer. Born in Kokomo, Ind., he received a bachelor's degree at the University of California at Los Angeles and a Ph.D. in astronomy at the University of California at Berkeley. He was on the staff of the Mount Wilson Observatory from 1931 to 1958 and served as associate director of the Griffith Observatory and Planetarium in Los Angeles from 1958 to 1964. Having begun to write articles and short stories in 1939, he found that writing was taking more and more of his time. So, he says, he "decided to take Nietzsche's advice to 'live dangerously'" and resigned to devote all his time to writing. He feels that he is in a particularly good position to assist in improving "communication between scientists and humanists."

J. W. L. KÖHLER ("The Stirling Refrigeration Cycle") is assistant director of the Philips Research Laboratories at Eindhoven in the Netherlands. He joined the laboratories in 1934, after obtaining undergraduate and graduate degrees at the University of Leiden. His university experience included some of the early work on cryogenics, a field to which he returned in 1946 when he became director of the group studying the Stirling refrigeration cycle at the Philips Laboratories. Actually he had sought to join the group studying the possibilities of the Stirling cycle for a hot-air engine and was disappointed to find that the only vacancy was with the refrigerator group. "At that time," he writes, "I could not foresee the extension of the Stirling cycle to the cryogenic range. It turned out that the job exactly fulfilled my ambitions for really fundamental problems on the one hand and, on the other, for designing mechanical products."

FRANK A. BEACH, who in this issue reviews *A Model of the Brain*, by J. Z. Young, is professor of psychology at the University of California at Berkeley.

Dear Sir,

In a day and age when the advance of human technology has reached such a tremendous peak, I wish to pay tribute to the telephone and to its magnificent contribution to our well proportioned way of life.

As a child in the early 1930's I was reared beside telephones, cables, telephone poles and dedicated "linesmen", in Villa Mercedes, San Luis, Argentina. I am the daughter of the late Jerome E. Johns who was the superintendent of all the transandine land lines--the telephone cables that crossed the Andes--for All America Cables. In those days, my father covered many miles of rugged country on horse- or muleback.

Remote as we were in those days we were a link with the world for we had the only telephone for miles around. When help was needed people would say "El Americano tiene teléfono." The American has a phone. Or in other words, All America Cables will help.

In those days we were a vital force in the community, and many and countless were the errands of mercy "run" by this member of ITT. The American flag always flew proudly over the different buildings where All America had an office. Even in times of strife, my father was allowed to fly his proud flag, for he was the respected American who was representative of the good power of the telephone.

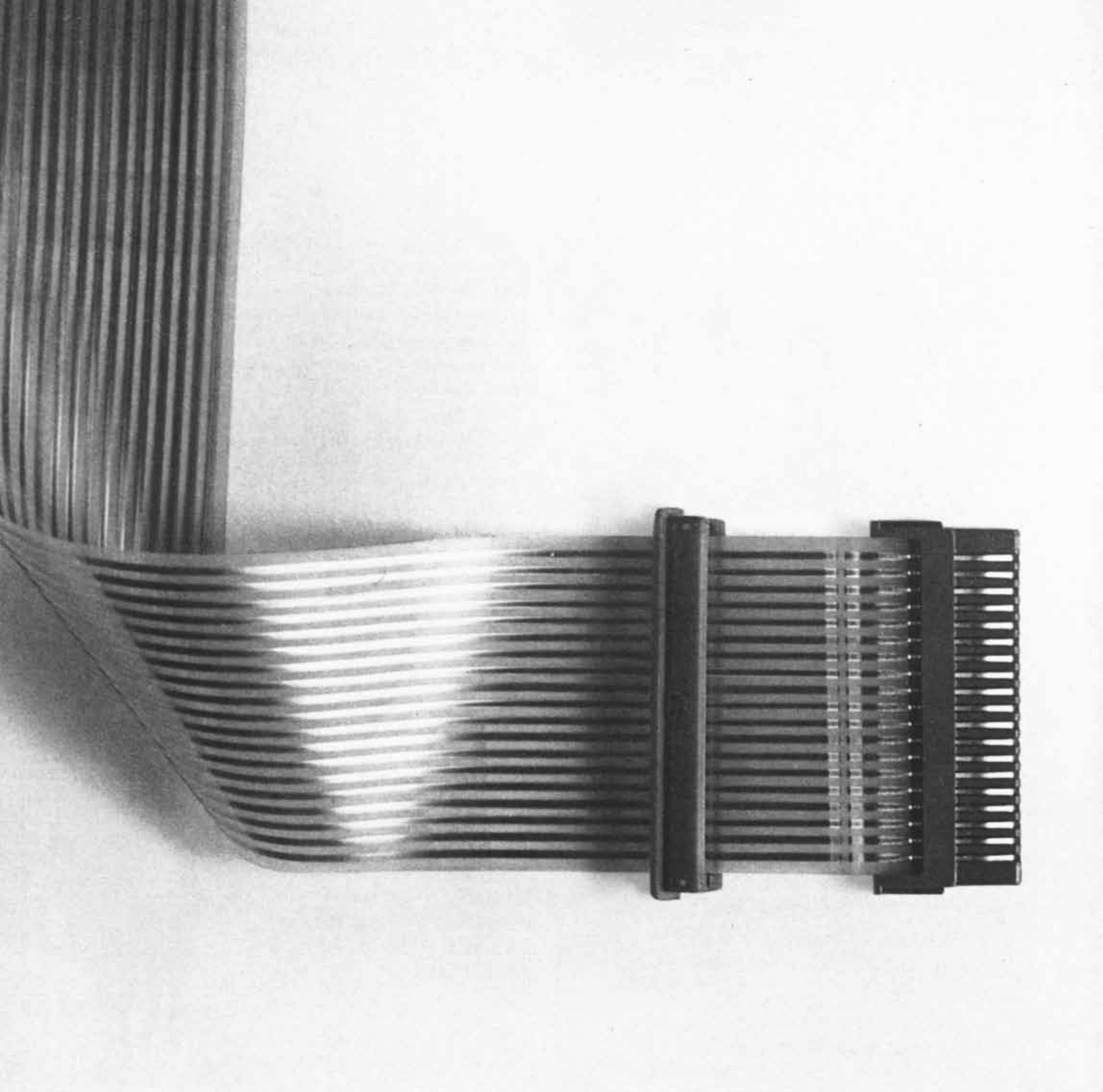
We had a small fire in our home the other day. I reached first for the telephone. Guess what I reached for after my children were safe? Not my sterling silver, not our hard-earned furniture or clothes. My hands fell lovingly on an old, old album with some very old pictures. Somehow they are the proudest things I own. Here are some of them for you to see.

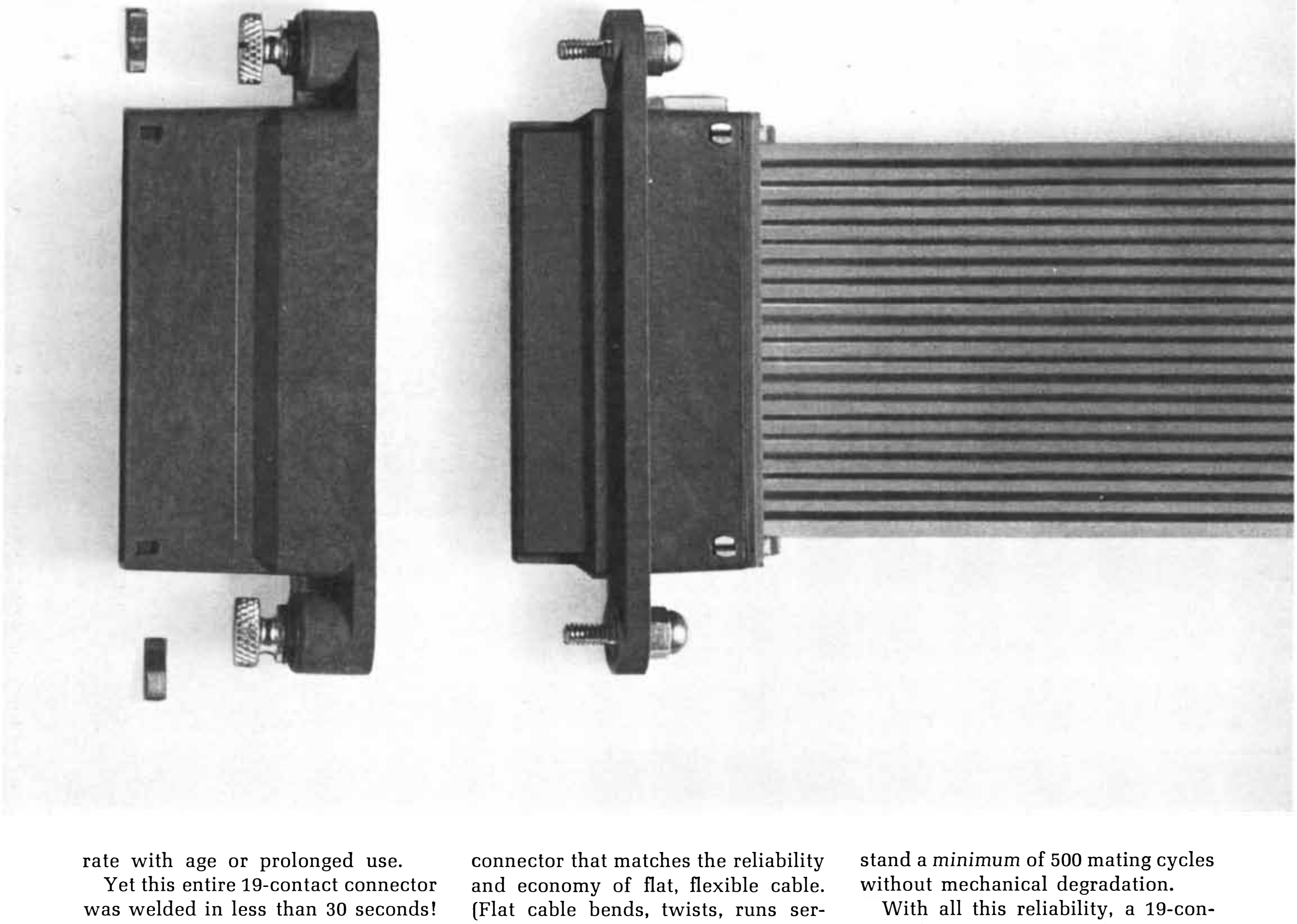
Very sincerely yours,
Caroline B. Crawford
(nee Johns)

"Remote as we were in those days we were a link with the world"

Mrs. Caroline B. Crawford said it. The pioneer spirit of men such as her father characterizes ITT and our 185,000 people. Today, as in the past, many of them work in remote areas of the world—as well as on the frontiers of the communication sciences. Thank you for your letter, Mrs. Crawford, and for allowing us to reproduce it here. International Telephone and Telegraph Corporation, 320 Park Avenue, New York, N.Y.

ITT





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The Structure of the U.S. Economy

The input-output tables on the next seven pages divide the economy into 81 sectors and list the transactions among them. The numbers are the constants of the technological relations among the sectors

by Wassily W. Leontief

"Gross national product," "Total output," "Value added by manufacture," "Personal consumption expenditures," "Federal Government expenditures," "Exports"—these headings in the book of national accounts describe the familiar external features of the economic system. In recent years the students and the managers of the system have been confronted with many questions that cannot even be clearly posed in such aggregative terms. To answer them one must now look "under the hood" at the inside workings of the system. In the fiscal agencies of many governments, in universities and in large industrial organizations in this country and abroad the needed insight is being supplied by the technique of "input-output" analysis. This technique reckons with the intermediate sales and purchases—that is, the outputs and inputs—that carry goods and services from industry to industry, from manufacturer to distributor and on to their final purchaser in the market. The technique thus ties predictions about the external configuration of the system to the indirect flows of supply and demand within. Input-output analysis of the U.S. economy has recently taken a major step forward with the publication by the Office of Business Economics in the U.S. Department of Commerce of the preliminary results of a study of the interindustry relations of the system as of the year 1958. The report features an input-output "table" that breaks down the system into 81 industries or functional economic sectors.

The Federal Government is charged by the Constitution itself with the task of taking a decennial census. Ever since the first census of 1790 Federal statistical agencies have maintained the tradition of keeping a comprehensive quantitative record of the country's social and economic progress. As the economy has grown in complexity and size, so have the variety and volume of data collected. It was not until the end of World War I, however, that the collecting agencies undertook to organize the data in accordance with some distinct picture of the economic system. The conceptual framework for the specification of the national accounts was supplied by the aggregative models of prevailing economic theory. That framework has evolved over the years as theory has evolved and today shows the pervasive influence of the ideas of the great British economist John Maynard Keynes.

The need for finer-grained information was felt acutely by the administrators of the U.S. industrial production effort during World War II. Given President Roosevelt's order for "50,000 airplanes," it was easy enough to predict that the country would have to produce more aluminum. It was not immediately apparent, however, that the building of aluminum potlines would collide with a shortage of copper—a shortage ultimately met by borrowing silver from Fort Knox to make the massive bus bars that delivered electricity to the potlines. As the locus of concern in the war-production effort shifted from the Office of Production Management to the administration of the Controlled Materials Plan in 1943 and 1944, officials were grateful to have at hand an input-output table of the U.S. economy for the year 1939. This was the first input-output table prepared under official Government sponsorship. It broke the system down into 95 sectors. (The author had constructed and published in 1936 tables of 42 sectors for the years 1919 and 1929.) The technique appeared promising enough, however, to encourage the Air Force and the Bureau of Labor Statistics in the Department of Labor to join forces after the war in Project Scoop. At a cost of $1.5 million a 200-sector input-output table of the economy was constructed for the year 1947, based on detailed statistical studies of transactions among 450 industrial sectors [see "Input-Output Economics," by Wassily W. Leontief; SCIENTIFIC AMERICAN, October, 1951].

After such an auspicious beginning the publication in late 1964 of a table of only 81 sectors for the year 1958, on a reported budget of less than $1 million, would seem a step backward. But the 1958 table does constitute progress in the input-output analysis of

Group	Sector	No.	1 Footwear and other leather products	2 Miscellaneous furniture and fixtures	3 Household furniture	4 Tobacco manufactures	5 Apparel	6 Miscellaneous fabricated textile products	7 Drugs, cleaning and toilet preparations	8 Food and kindred products	9 Special industry machinery and equipment	10 Ordnance and accessories	11 Aircraft and parts	12 Miscellaneous transportation equipment	13 Radio, television and communication equipment	14 Materials-handling machinery and equipment	15 Miscellaneous manufacturing	16 Optical, ophthalmic and photographic equipment	17 Service-industry machines	18 Household appliances	19 Scientific and controlling instruments	20 Office, computing and accounting machines	21 Farm machinery and equipment	22 Engines and turbines	23 Construction, mining and oil-field machinery	24 Miscellaneous electrical machinery, equipment and supplies	25 Metalworking machinery and equipment	26 Motor vehicles and equipment	27 General industrial machinery and equipment	28 Electric lighting and wiring equipment	29 Electric industrial equipment and apparatus	30 Electronic components and accessories	31 Heating, plumbing and structural metal products	32 Machine-shop products	33 Metal containers	34 Stampings, screw machine products and bolts	35
FINAL NONMETAL	Footwear and other leather products	1	83.50	0.01	0.31		0.78	2.63	0.01		0.01	0.04	0.01	0.01	0.01	0.01	6.15	0.49	0.01	1.26	0.90	0.02	0.01	0.01	0.01	0.01	0.06		0.01	0.01	0.02	0.02	0.01	1.27		0.28	0.0
	Miscellaneous furniture and fixtures	2	0.01	19.83	7.48			2.64			0.02		1.70	4.25	0.01	0.46	0.94		0.87	0.28	3.72	0.23	0.63					0.20	0.13			0.02	1.62			0.14	1.0
	Household furniture	3	0.32	28.24	14.88			2.98			0.05	0.02		6.83	23.52		0.28		1.11	0.17	0.63		0.04		0.16		0.03	0.05	0.35	0.01		5.38	1.00		0.02	0.27	1.2
	Tobacco manufactures	4				191.49				0.01							0.11																				
	Apparel	5	5.62	1.02	0.34		172.18	8.74	0.35	0.61	1.01	0.59	0.89	1.08	0.75	0.72	1.63	0.86	0.71	0.71	2.77	0.86	0.74	0.69	0.75	0.93	1.09	0.45	0.93	0.98	0.91	1.33	0.89	1.31		1.06	1.0
	Miscellaneous fabricated textile products	6	0.45	0.99	1.28		12.57	62.31	0.50	1.56				0.43	0.01		1.28		0.05		0.36							6.69					0.31			0.14	0.0
	Drugs, cleaning and toilet preparations	7	0.33	0.04	0.03	1.27	0.09	0.73	62.67	3.33	0.70	0.60	0.40	0.61	0.34	0.69	2.80	0.07	0.68	0.18	2.01	0.21	0.61	0.45	0.51	0.07	0.40	0.81	0.42	0.17	0.11	0.06	0.26	0.62	2.35	0.66	0.3
	Food and kindred products	8	0.25	0.07	8.46	5.98		0.06	29.47	165.58	0.40					0.09	1.47		0.09	0.01	3.30		0.06														0.0
FINAL METAL	Special industry machinery and equipment	9	0.01	0.39	2.87				1.38		49.94	1.16	0.43	0.27	0.33	4.27	0.38	1.30	2.82	0.02	1.74	5.41	2.87	1.14	1.82	0.02	8.42	0.25	6.76	0.01	1.14	0.38	3.62	6.30		0.52	2.5
	Ordnance and accessories	10							0.02		0.80	17.83	51.74		24.38		0.09	1.30		0.01	29.31	1.13	2.66		0.32		0.28	0.27	0.13	0.01	1.31	8.31	0.12	0.04		0.68	0.1
	Aircraft and parts	11	0.08	1.00	0.05			0.31			3.52	206.60	190.20	4.57	8.57	1.85	0.77	0.06	6.45	0.14	16.12	6.77	2.15	9.97	0.65	0.72	5.51	0.39	16.70	0.01	1.08		1.49	3.15	3.34	1.56	0.1
	Miscellaneous transportation equipment	12	0.03	0.67	0.01						3.19	3.54	0.22	67.49	0.17	3.98	2.07	0.52	0.44	1.95	1.43		2.05	9.09	4.86	0.02	0.28	0.89	5.08	0.01	5.09		7.09	3.15		0.27	0.1
	Radio, television and communication equipment	13		1.34	0.30						9.17	34.44	27.09	1.59	57.97	0.19	2.54	4.54	2.89	0.28	10.75	9.40	0.09	0.09	0.65	4.56	0.06	5.23	1.87	2.19	10.11	33.88	0.12	0.63		0.27	0.3
	Materials-handling machinery and equipment	14	0.02	0.04	0.61						4.80	0.01	0.39	4.28	0.01	37.54	0.01		1.11			0.02	0.41	1.26	5.51		2.37	0.22	7.61	0.01	0.39		1.00	0.38		0.27	1.0
	Miscellaneous manufacturing	15	3.74	15.22	4.70	1.11	18.17	16.60	0.81	0.48	0.92	2.57	1.76	2.44	1.70	27.40	55.01	1.73	1.58	1.14	5.54	1.42	1.01	1.31	0.57	0.55	2.47	0.86	0.28	5.19	0.45	1.57	0.93	0.32	0.72	5.08	3.1
	Optical, ophthalmic and photographic equipment	16	0.97	0.01					0.05		1.96	0.70	2.05	0.10	2.40	0.07	0.01	55.54	0.07	1.46	5.62	0.10	0.07	0.06	0.07	0.41	0.14	0.04	0.26	0.09	0.67	0.32	0.14	0.17	0.06	0.50	0.1
	Service-industry machines	17		9.37	0.07			0.01	0.23		4.80	3.95	0.63	2.43	0.65	1.85	0.29		47.02	29.02	1.64	0.01	0.41	0.09	0.65	0.03	1.93	1.29	8.68	0.87	0.32	0.01	8.28	0.63		1.76	1.3
	Household appliances	18		0.67	1.12				0.15		1.20	0.21	2.21	5.10	0.33		2.07		63.85	10.71	0.86		3.65	0.04	0.16	2.61	1.93			0.31	0.59	0.76	6.77	0.08	2.48	2.40	2.0
	Scientific and controlling instruments	19	1.77	6.02	0.04		0.14	3.07	3.88		1.77	22.58	15.52	1.39	5.55	0.52	1.33	54.09	12.70	30.20	57.85	3.44	1.35	0.83	0.69	4.01	0.90	4.38	6.15	2.66	13.19	4.74	8.89	1.32	0.19	1.88	3.2
	Office, computing and accounting machines	20		2.03				0.01	0.01		1.52	0.86	0.46		1.17	1.02	2.64	0.52	0.08	0.01	13.12	87.08			0.32	0.59	0.02		0.03		0.59	4.72	0.31	0.63		0.62	0.1
	Farm machinery and equipment	21	0.07	0.67							2.79	1.07	0.16	5.10		4.62	0.32		0.44	0.01	0.34	0.02	37.77	13.84	17.55	0.65	1.54	1.05	2.14	0.31	0.20		1.74	0.63	0.05	1.09	1.0
	Engines and turbines	22									0.49	1.04	1.56	30.51		14.07	0.01		1.56		0.01		49.29	91.68	25.89	1.17	1.82	3.79	12.93		15.88		3.97	5.04		1.50	1.0
	Construction, mining and oil-field machinery	23		0.33							7.57	0.43	0.16	5.32	0.17	49.82	0.01	0.26	0.49	0.31	0.63	0.01	12.87	27.73	55.93	1.43	1.92	0.44	7.35	0.31	1.12	0.76	2.99	3.15		0.27	2.5
	Miscellaneous electrical machinery, equipment and supplies	24	0.02	0.02	0.02	0.01		0.02	0.03	0.06	0.42	0.29	3.59	1.21	0.34	2.28	0.19	3.58	0.01	0.28	0.92	0.45	7.84	17.68	1.54	37.25	0.09	15.43	0.98	29.12	2.23	0.76	0.05	1.91	0.01	0.28	0.3
	Metalworking machinery and equipment	25	0.09	2.64	0.99	0.06	0.01	0.18	0.12	0.21	23.14	11.20	19.42	5.18	4.60	16.11	0.78	4.40	2.95	7.75	12.18	9.34	18.04	16.83	16.96	14.13	57.00	11.26	17.78	5.62	11.65	5.74	5.45	18.12	12.26	11.44	26.5
	Motor vehicles and equipment	26	0.04	2.34	0.04				0.03		2.75	4.30	6.41	13.43	0.17	9.25	1.13		12.45	2.09	14.58	0.05	16.62	25.64	14.64	34.45	47.54	297.57	6.28	0.01	1.57		3.98	4.03	0.02	26.58	4.8
	General industrial machinery and equipment	27	0.11	1.67	0.30	0.03	0.01	0.49	0.05	0.03	55.27	6.35	10.85	15.50	1.36	67.59	1.01		15.55	10.83	5.84	6.45	57.56	32.16	57.17	16.69	32.64	5.70	68.73	1.47	8.83	1.00	11.51	9.57	6.81	0.70	8.3
	Electric lighting and wiring equipment	28	0.73	0.88	0.94	0.10		0.04	0.04	0.35	0.49	11.79	1.30	3.49	11.49	2.81	3.00	3.90	6.49	7.82	3.33	4.05	0.71	0.46	1.11	37.38	0.60	4.20	1.07	40.25	16.83	7.98	2.06	0.79	0.42	4.01	2.2
	Electric industrial equipment and apparatus	29	0.03	0.32	0.16	0.01	0.01		0.04	0.12	38.58	21.98	3.37	33.51	16.70	48.66	5.81	13.33	88.79	41.59	34.23	23.26	6.21	17.33	11.26	23.65	27.27	2.17	51.46	34.29	66.85	33.19	11.38	4.96	1.03	4.20	3.8
	Electronic components and accessories	30	0.61	0.11	0.30			0.01			2.59	0.72	6.01	0.09	181.09	0.44	2.01	0.14	0.06	0.07	29.03	41.72			0.16	13.47	0.09	0.79	0.30	3.50	27.52	61.04	1.00	0.08		0.93	0.7
BASIC METAL	Heating,		0.12	12.71	3.18			0.01	0.04		10.88	1.93	0.61	45.96	0.64	12.10	0.38		23.16	15.76	1.28	0.02	2.46	1.19	15.75	0.02	3.74	1.02	18.41	2.30	2.86	0.45	18.71	1.89	4.77	7.98	8.8
	Machine-shop products	32	0.09	0.18	0.11	0.02		0.07	0.02	0.01	4.03	79.90	9.93	3.56	0.93	15.73	2.26	0.65	0.89	0.98	7.46	2.47	15.03	30.13	4.52	8.08	6.12	6.44	5.76	1.61	1.75	1.03	4.13	67.46	4.75	3.76	3.0
	Metal containers	33			0.01	1.31			16.31	23.88	0.01								0.01		2.42				0.04		0.28			0.01			0.41		1.55	3.53	0.1
	Stampings,		0.56	7.27	5.19	0.06		0.28	3.24	2.73	12.59	6.64	19.34	4.95	18.64	17.54	13.56	6.12	35.15	53.64	17.91	11.08	32.85	22.17	10.38	24.36	26.72	31.03	11.13	27.38	14.98	23.30	19.29	5.16	13.31	27.13	19.
	Other fabricated metal products	35	7.68	36.46	60.51	1.51	1.21	1.98	8.79	1.34	16.62	10.32	10.32	21.10	11.94	21.23	17.42	10.20	26.41	33.09	16.43	6.00	6.93	2.58	12.97	4.58	20.62	36.03	19.11	17.47	8.44	13.49	31.53	21.09	3.97	26.59	38.4
	Primary nonferrous metal manufacturing	36	0.40	13.25	8.51	1.15		0.03	0.15	0.56	44.83	48.35	28.35	18.37	19.55	11.69	46.67	27.52	50.83	42.51	39.96	18.82	7.84	32.87	7.15	106.07	29.32	11.44	28.29	51.86	72.36	44.84	73.00	77.55	9.57	65.25	67.8
	Nonferrous metal ores mining	37							0.07												0.43					1.04				1.46							0.2
	Primary iron and steel manufacturing	38		93.10	24.04		0.07	0.35	0.12	0.02	89.34	13.25	31.93	118.80	9.27	108.61	27.52	5.98	68.49	76.47	19.28	22.25	150.27	101.77	153.98	29.10	76.27	87.80	106.74	67.75	57.95	20.28	238.96	79.99	439.12	200.59	195.
	Iron and ferroalloy ores mining	39																								1.27	0.18				0.63						
BASIC NONMETAL	Stone and clay products	40	2.33	1.72	2.58	0.01	0.01		1.83	0.04	4.37	2.72	3.76	8.26	3.16	3.79	2.34	19.07	5.94	7.79	3.52	2.69	5.68	6.53	5.78	9.41	7.38	2.79	9.21	6.70	7.84	6.95	6.23	17.42	1.97	7.79	7.0
	Stone and clay mining and quarrying	41							0.56	0.06				0.07			0.08				0.03		0.16		0.12	0.17		0.01	2.43				0.18	0.03			0.1
	Printing and publishing	42	5.46	1.01	0.36	2.18	0.95	1.24	4.10	1.93	0.97	2.03	0.81	0.50	1.45	0.56	5.30	0.26	0.23	0.64	0.56	3.28	0.48	1.47	0.42	0.21	0.08	0.54	0.54	0.32	1.18	0.55	0.53	0.19	3.01	1.43	2.
	Glass and glass products	43	0.08	37.23	14.09			0.01	20.09	9.48	0.05	0.91	0.13	5.11	4.55	0.30	5.16	11.19	2.76	1.83	3.21	0.26	0.12	0.53	0.03	0.65	0.14	10.29	0.05	28.99	0.89	31.83	3.73	0.05	0.02	1.02	0.
	Paperboard containers and boxes	44	12.40	18.59	18.49	11.87	6.20	9.64	30.47	13.81	0.30	3.42	0.75	0.34	5.20	0.36	38.50	6.81	8.32	9.83	7.91	1.75	2.23	4.78	0.87	7.06	0.28	1.07	1.65	17.72	3.91	5.55	3.94		13.37	9.23	5.
	Paper and allied products, except containers	45	8.59	3.39	3.56	11.77	0.98	12.70	8.72	5.82	2.15	1.48	0.40	1.68	4.45	0.65	22.16	33.01	3.94	1.50	4.99	6.81	0.61	1.12	0.91	1.28	0.01	3.65	2.75	2.78	7.88	11.79	1.83	0.09	4.35	4.49	3.8
	Wooden containers	46	0.32	0.05	0.13	1.57				1.54	0.14	0.96				0.01	0.35		5.09	5.70	0.29	0.34	0.30			0.02			0.06		0.03		1.00		0.48	0.47	0.8
	Lumber and wood products except containers	47	8.74	59.47	124.21	0.22		0.01	1.04	0.06	5.60	0.24	1.71	24.33	1.80	0.77	18.68	0.07	3.27	1.59	0.77	0.54	3.69	0.27	1.24	0.02	1.40	0.55	1.44	1.24	1.27	0.26	2.36		0.41	5.13	8.1
	Forestry and fishery products	48					9.84	0.38		4.32							0.54																				
	Miscellaneous textile goods and floor coverings	49	13.37	17.16	13.20		5.56	72.98		0.01		0.10	0.49	0.72			6.51	0.31		0.07	1.80			0.21				3.92		0.01	0.31		0.04			0.11	1.1
		50	59.16	9.10	40.45	1.66	1.64	29.54	9.56	2.26	12.50	24.29	6.23	8.92	9.87	18.90	35.66	7.42	11.61	32.66	11.84	10.82	33.89	4.88	15.01	46.59	3.94	28.66	4.12	15.36	7.28	6.65	1.38	1.78	14.59	6.58	7.1
	BR	51	25.81	1.92	56.85	0.19	274.20	442.22	0.10	0.12	1.28		0.15	0.61	0.25	1.50	18.50	0.53	0.11	2.53	7.89	0.06	0.06	0.09	0.08	0.33		2.21	0.56		0.29		0.24			0.08	0.0
	Paints and allied products	52	0.01	16.40	20.34	0.02	0.02	0.18	2.07	0.09	0.32	0.49	0.82	7.99	0.44	2.52	7.42	0.20	4.97	5.78	0.52	0.98	4.00	1.19	1.45	0.01	0.05	3.89	0.67	4.79	2.89	0.63	2.67		18.72	4.99	1.
	Leather tanning and industrial leather products	53	208.93	1.35	1.16	0.04	2.63	0.01			1.22			0.44	0.18	0.10	6.31	0.07	0.14	0.24	0.74	0.10	1.10	0.14	0.13	0.07	0.07	0.29	0.25	0.17	0.11	0.05	0.13	0.32	0.37	0.12	0.1
	Livestock and livestock products	54							0.73	233.13																											
	Miscellaneous agricultural products	55				184.04	0.59		0.37	75.15							1.38				1.24																
	Agricultural,																						1.27														
	Plastics and synthetic materials	57	0.66	1.11	0.34	17.81	10.25		2.39	0.22	0.73		0.68	7.28	6.95	0.49	22.82	0.70	1.00	2.60	2.44	1.17	0.16	0.65	0.47	5.59	0.44	1.16	0.27	18.65	6.90	7.65	0.33		0.97	4.02	0.1
	Chemicals and selected chemical products	58	0.32	0.16	0.06	0.87	2.97	0.12	125.92	3.45	2.12	2.25	1.23	2.27	1.02		8.41	61.60	6.42	5.09	3.05	0.36	1.01	0.06	0.91	21.46	0.97	1.79	1.77	5.49	3.81	11.45	2.47		0.02	3.26	9.8
	Chemical and fertilizer mineral mining	59					0.02		0.01	0.13							0.01																				0.0
ENERGY	Petroleum refining and related industries	60	0.31	2.01	2.12	0.45	0.40	0.94	9.58	4.44	5.67	2.19	2.39	4.39	1.24	3.35	3.16	2.68	2.95	1.28	1.33	1.51	4.00	3.98	4.39	1.39	5.05	2.09	3.71	1.80	3.14	1.59	5.29	10.10	2.71	6.37	4.5
	Electricity, gas and water	61	3.33	3.27	3.81	0.96	3.16	3.45	4.03	5.57	5.56	3.79	5.44	6.34	2.69	3.94	4.98	3.71	4.98	6.04	3.85	3.34	5.59	4.30	6.10	6.17	6.12	4.74	6.06	5.31	6.86	7.42	6.21	7.87	6.64	8.97	7.4
	Coal mining	62			0.65	0.23	0.05		0.58	0.63	0.01		0.18	0.70	0.30		0.14	1.60	0.33	0.33			0.96	1.03	0.66			0.65	0.20		0.33	0.16	0.22	0.13	0.18	0.37	0.2
	Crude petroleum and natural gas	63																																			
SERVICES	Federal government enterprises	64	2.25	0.98	0.58	2.13	1.81	1.36	2.14	0.47	0.95	0.86	0.94	0.77	2.39	1.23	1.81	2.14	1.06	2.09	1.14	1.55	1.93	0.99	0.78	2.29	0.79	1.70	1.01	1.50	2.48	3.29	1.01	1.22	0.70	1.03	0.
	Transportation and warehousing	65	11.93	17.12	22.14	12.08	8.32	9.36	18.84	40.20	11.23	10.70	8.83	17.50	11.49	11.92	15.31	14.38	14.94	15.82	9.68	8.31	18.35	12.39	14.33	12.90	7.83	18.66	13.18	13.39	11.90	10.55	17.75	9.75	25.31	15.37	13.
	State and local government enterprises	66	0.09	0.16	0.19	0.06	0.09	0.28	0.23	0.46	0.19	0.14	0.16	0.22	0.10	0.08	0.24	0.10	0.16	0.19	0.14	0.10	0.32	0.15	0.15	0.23	0.12	0.18	0.16	0.19	0.17	0.18	0.22	0.18	0.09	0.27	0.
	Hotels, personal and repair services except automobile	67	2.90	1.64	2.11	0.42	2.56	1.55	0.51	0.59	1.48	0.84		1.55	1.05	1.06	1.81	1.25	0.99	0.99	1.34	1.20	1.07	0.97	1.05	1.28	1.57	0.66	1.25	1.36	1.27	1.92	1.24	1.90	0.86	1.47	1.
	Automobile repair and services	68	0.37	1.84	1.67	0.31	0.24	1.22	0.59	4.41	1.47		0.13	0.92	0.22	0.67	1.47	0.57	1.11	0.18	0.25	0.26	1.04	0.29	0.85	0.46	0.69	0.36	0.73	0.31	0.49	0.02	2.06	1.23	0.40	0.01	0.
	Radio and television broadcasting	69																																			
	Amusements	70	0.06	0.04	0.05	0.01	0.05	0.03	0.02	0.02	0.04	0.03		0.03	0.03	0.03	0.04	0.03	0.03	0.02	0.04	0.03	0.03	0.03	0.03	0.03	0.04	0.01	0.03	0.03	0.03	0.04	0.03	0.04	0.02	0.03	0.
	Medical and educational services; nonprofit organizations	71	1.16	1.01	1.09	1.00	1.15	0.91	0.97	1.00	0.99	0.98	0.91	1.05	1.01	0.89	1.06	1.04	0.93	1.00	0.98	0.87	1.01	0.95	0.99	0.96	0.94	1.01	0.96	1.02	1.00	1.03	0.99	1.05	1.02	0.99	0.
	Wholesale and retail trade	72	27.17	53.66	55.36	13.05	35.35	45.68	26.52	36.38	38.55	29.12	18.04	47.74	35.04	42.25	58.78	35.84	54.24	42.11	37.98	48.43	40.84	26.86	35.24	33.87	28.21	30.11	45.37	62.88	30.28	54.70	36.12	30.77	38.69	29.20	34.
	Finance and insurance	73	7.39	5.19	5.31	2.03	6.63	4.43	7.92	5.30	7.08	6.47	2.98	5.10	3.36	7.72	8.26	5.47	8.03	3.26	5.07	5.18	6.52	5.92	7.01	4.05	7.71	3.80	6.17	4.36	4.45	4.79	7.96	8.19	6.20	7.93	6.7
	Communications, except radio and television broadcasting	74	2.95	4.06	5.24	0.39	3.01	2.37	2.12	2.49	9.67	4.45	4.45	2.77	3.35	3.44	5.50	3.10	3.46	4.14	4.46	4.25	2.53	2.55	3.20	3.27	8.17	2.07	9.00	2.66	4.11	2.83	4.01	6.81	1.00	2.58	2.
	Business services	75	28.29	9.88	16.73	45.00	9.4	6.27	151.34	25.10	12.06	10.89	3.45	8.68	22.94	15.02	23.28	57.88	9.68	65.41	14.87	26.02	26.90	11.52	13.79	21.45	10.40	25.14	11.70	13.26	1113	10.14	11.37	10.27	9.31	9.19	14.
	Real estate and rental	76	9.16	10.75	12.13	1.27	11.37	10.56	8.49	4.56	9.84	4.42	5.68	4.54	6.06	9.28	14.90	13.13	12.89	5.25	10.03	7.78	5.38	4.53	5.46	7.32	17.54	2.77	7.07	9.44	7.78	20.13	6.17	14.85	4.12	8.41	5.5
	Maintenance and repair construction	77	0.13	0.30	0.57	0.05	0.56	0.15	0.26	3.66	0.96	1.63	1.79	0.37	1.39	0.32	2.93	0.34	1.20	0.63	0.16	0.73	0.74	0.32	0.23	0.07	2.13	3.11	1.16	0.06	1.32	0.76	0.91	4.11	0.25	0.64	0.
	Research and development	78								0.08			0.95		0.33			1.30						5.46				0.53				0.76	0.25				
	Office supplies	79	0.97	0.93	0.78	0.15	0.70	0.56	0.46	0.43	0.99	1.06	0.78	0.86	1.07	0.93	1.13	0.72	0.74	0.57	1.42	1.42	0.82	0.72	0.76	0.80	0.84	0.38	0.94	0.75	1.24	1.19	0.52	0.78	0.26	0.74	0.
	Business travel, entertainment and gifts	80	6.91	10.22	8.63	1.73	6.71	6.87	7.09	5.41	13.87	19.89	4.11	10.33	18.14	13.00	12.84	10.37	10.42	9.60	22.97	23.61	8.75	10.04	10.63	13.62	11.81	4.24	13.24	12.71	21.00	20.23	8.62	10.97	3.57	10.13	10.
	Scrap, used and secondhand goods	81						0.54			1.40	0.01	0.45	2.42	064	0.15	0.92		0.12	0.16	0.03	0.19	2.73	2.37	0.81	0.23	0.57	0.37	2.37	0.85	0.10		4.23	1.85			2.
	Noncompetitive imports				0.15	0.01	0.57		1.92	23.37	2.47						16.35	0.			0.20						3.59	0.01			1.21	2.30					
	Value added		440 79	447 37	4 5 99	48232	386.69		9		9	9													4		1	98 41	43604								
			1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35

COEFFICIENT TABLE is one way to present transactions among 81 sectors of economy. Sectors are listed vertically at left and are repeated horizontally at top. Reading horizontally across one sector, the coefficients in each cell govern outputs, or sales, to

Row	36 …ING	37 …ORES MINING	38 …STEEL MANUFACTURING	39 …AND FERROALLOY ORES MINING	40 STONE AND CLAY PRODUCTS	41 STONE AND CLAY MINING AND QUARRYING	42 PRINTING AND PUBLISHING	43 GLASS AND GLASS PRODUCTS	44 PAPERBOARD CONTAINERS AND BOXES	45 PAPER AND ALLIED PRODUCTS, EXCEPT CONTAINERS	46 WOODEN CONTAINERS	47 LUMBER AND WOOD PRODUCTS, EXCEPT CONTAINERS	48 FORESTRY AND FISHERY PRODUCTS	49 MISCELLANEOUS TEXTILE GOODS AND FLOOR COVERINGS	50 RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS	51 BROAD AND NARROW FABRICS, YARN AND THREAD MILLS	52 PAINTS AND ALLIED PRODUCTS	53 LEATHER TANNING AND INDUSTRIAL LEATHER PRODUCTS	54 LIVESTOCK AND LIVESTOCK PRODUCTS	55 MISCELLANEOUS AGRICULTURAL PRODUCTS	56 AGRICULTURAL, FORESTRY AND FISHERY SERVICES	57 PLASTICS AND SYNTHETIC MATERIALS	58 CHEMICALS AND SELECTED CHEMICAL PRODUCTS	59 CHEMICAL AND FERTILIZER MINERAL MINING
					BASIC NONMETAL																			
1					0.04		0.04	0.01	0.14	0.11	0.01	0.07	0.01	0.42	1.13	0.03	0.01	2.16	0.03	0.16			0.01	0.01
2	0.01						0.40			0.16	1.12	0.38			0.15							0.01		
3			0.08					2.33		0.02	6.07	2.33		2.89	0.07	0.02						0.01		
4									0.01	0.01														
5	0.56		0.78					1.23	0.89	0.72	0.02	1.34		3.21	2.64	1.55	0.40	0.01				0.46	0.44	
6	0.22		0.11		0.44			0.01	0.09	2.52		0.19		5.55	0.44	3.21		1.59	0.32	1.51			2.48	
7	1.06	0.10	1.86	0.01	6.12	0.13	0.49	1.54	1.60	2.21	0.56	1.15		0.48	0.92	2.19	10.86	25.85	1.10		0.03	10.72	12.84	0.20
8	0.07		0.36		0.83				0.06	8.04		0.01	21.54	7.05	0.20	2.21	31.46	235.75	113.42	0.12	4.82	4.13	11.59	0.12
9	0.22	0.01	1.28		0.82		2.77		3.68	2.98	4.00	1.64		0.72	0.80	5.97	0.02					1.31	9.82	
10	0.16		0.06				0.44		0.36									0.06						
11	0.02		0.06		0.13		1.35					0.03		0.32	2.47								0.08	
12	0.63		0.84	3.08		0.18	0.03				0.26	0.89	17.78		0.29					0.13				0.42
13	0.91		0.01	1.58	0.03		0.40								0.66							0.24		
14	0.11	0.13	0.13	0.03	0.02	15.10						0.48			0.02								0.49	6.18
15	1.50	0.01	0.61	0.02	2.49	0.39	2.61	0.90	0.94	0.99	0.48	1.64	2.00	8.73	4.53	1.57	0.71	0.62	0.04	0.02	0.32	0.60	1.53	0.24
16	0.05	0.07	0.08	0.08	0.10	0.07	3.98	0.13		0.31					0.30	0.03	0.04	0.09				2.38	0.46	0.07
17	0.22		0.08		0.07			0.20		0.04					0.02								0.08	
18	0.44		0.13					0.39	0.07						0.44							0.02		
19	0.44	0.41	0.27	0.25	0.48	0.22	0.13	0.92		0.31		0.02		0.02	1.38	0.02	0.12	0.32				0.19	0.27	0.22
20			0.06				0.38			0.18													0.59	
21	0.04		1.41		0.04	0.01		0.22				0.03		0.41	0.01		0.13		0.19	8.46			0.02	
22	0.01	0.51	0.13	0.48									0.11		0.01									0.35
23	0.01	28.03	0.76	30.19	0.07	50.24	0.03								0.01									30.51
24	5.5	0.16	0.01	0.29	0.05	0.19	0.01	0.05	0.01	0.02	0.09	0.10		0.01	0.15	0.01	0.02	0.01	0.28	0.91		0.01	0.03	0.12
25	7.84	0.69	6.73	0.10	1.24	0.07	0.11	1.51	0.59	0.85	0.32	0.16		0.22	0.61	0.20	0.10	0.70				1.32	0.70	0.02
26	1.55	0.96	1.88	0.68	0.20	4.01	0.16					0.06		0.41	0.02			0.06	0.91	1.48			0.01	2.60
27	3.47	2.29	3.14	0.28	0.35	3.46	0.09	1.41	0.49	0.59	0.30	1.30		0.11	0.88	0.11	0.17	0.26				0.54	0.34	1.67
28	6.05	0.49	0.52	0.47	3.62	0.09	0.10	2.60	0.44	1.30	1.99	1.24	0.09	0.21	1.58	0.25	0.17	0.93	0.03	0.04		0.38	0.11	0.06
29	3.83	4.66	4.41	0.97	0.87	1.97	0.42	0.67	0.10	0.50		0.03		0.06	0.53	0.06	0.02	0.59				0.64	1.24	5.82
30	0.22				0.24		0.06								0.29									
31	0.33	0	2.51	1.48	0.67	0.01		0.42		0.04	0.52	0.38			0.44	0.05	0.53					0.24	0.17	0.21
32	3.66	0.09	7.55	0.09	0.47	0.33	0.05	0.68	0.26	0.37	0.32	0.33		0.03	2.64	0.02	0.09	0.15	0.07	0.12		0.27	0.36	0.20
33									3.90	0.05	0.05						46.69		0.20	0.64		1.20	7.13	
34	10.21	0.58	6.57	0.36	1.50	0.15	0.25	4.68	1.00	1.62	2.12	2.61		0.12	3.30	0.11	0.45	0.80	0.84			0.76	0.84	0.89
35	11.69	1.31	17.56	1.09	12.03	0.62	1.69	4.04	2.39	11.31	6.53	8.36	0.81	1.23	11.25	0.84	1.38	1.59	1.11	1.67	5.77	1.35	3.67	1.00
36	324.82	6.22	16.70	2.32	1.96	1.17	1.20	2.23	0.14	1.48		1.23		0.25	1.90	0.24	0.32	0.21	0.04	0.03		0.36	14.95	3.74
37	86.86	224.52	0.37	50.34	0.54	0.64		0.04				0.03					0.09						4.79	0.62
38	13.00	49.55	211.98	26.41	4.07	14.81			0.53	0.10	40.35	0.04		0.35	2.08	0.37	5.62						18.07	21.49
39	2.35	12.36	54.85	80.48	1.20	0.27																	4.73	0.73
40	5.15	5.95	15.63	1.02	121.85	67.14	0.01	29.11	0.06	5.16	1.53	4.09		0.90	3.55	0.19	9.84	9.57	0.04	1.09		0.41	3.15	0.59
41	0.48	0.07	2.86		65.95	7.83		11.54		3.72		0.02		0.02	0.87		0.46		0.03	2.88		0.12	1.63	19.12
42	0.98	0.39	1.50	0.06	2.05	0.34	126.64	1.53	6.85	10.59	2.15	4.00	0.08	0.53	3.13	0.78	2.38	1.96	0.19	0.31	0.02	1.00	2.57	0.06
43	0.03		0.06		0.79			49.63	1.88	0.05		1.25		0.84	6.42	2.20		0.04	0.13			0.27	1.52	
44	0.78		0.80		9.70	2.00	5.03	77.77	31.05	29.15	2.25	4.53	8.20	6.90	7.31	7.99	10.81	1.51	0.53	0.11	3.93	5.55	6.02	1.04
45	3.01	0.50	2.53	0.03	22.00	9.01	172.61	2.29	432.21	206.18	1.84	7.36	7.12	11.93	4.14	1.57	7.50	3.07			1.26	45.66	10.10	6.15
46			0.17		1.48			5.48	0.55	0.56	36.91	2.59						2.13		4.33	0.05	0.21	0.26	
47	1.12	1.30	1.04	7.55	1.77	0.02	0.04	15.54	0.82	69.33	375.32	301.86		0.02	1.63	0.12	0.80		0.07	0.07		0.23	2.61	0.48
48												99.24	13.92					1.11					1.26	
49	0.56		0.05		0.22	0.03	1.41	0.06		1.71		0.20	10.12	95.95	67.04	23.44		0.06	0.22	1.15	7.61	0.18	0.17	
50	1.80	3.67	3.23	0.79	10.35	19.47	1.20	3.91	8.90	15.01	1.23	6.72	7.46	16.06	30.29	4.05	2.99	9.49	0.81	6.74	1.17	17.78	7.11	5.58
51	1.65	1.77		0.19	1		0.06			6.14				189.47	21.19	347.29	0.21	0.06		0.31		0.94	0.08	0.38
52	0.80	0.19	0.80	0.01	1.16			0.05		0.27	0.91	4.76	1.61	0.54	0.18	0.35	1.57	0.02				6.26	3.62	
53					0.09									0.14	0.73	0.17		144.17					0.01	
54													65.21	24.82	20.73	9.80		59.18	180.35	73.79	138.24			
55					0.52							25.59	142.53	6.85		110.86			252.54	30.63	351.29		1.15	
56												1.00	15.20						18.85	38.01	1.05			
57	12.31		0.25		11.12				3.14	9.70		7.06		183.24	143.31	86.87	122.45					27.07	20.38	
58	10.65	40.44	9.68	16.46	21.35	11.63	14.35	38.98	2.37	35.14	0.02	7.56	0.15	3.31	47.04	15.64	229.65	71.11	1.31	49.52	0.20	344.07	199.73	36.95
59	0.20	1.17	0.39		3.03	0.45		0.30		1.65		0.01	0.06	0.01	1.11	0.07		0.97		1.23		0.12	29.81	68.42
60	4.55	7.97	7.71	13.01	11.39	30.11	0.89	3.17	6.81	12.86	6.19	9.57	16.44	1.94	2.42	2.45	9.01	4.07	1.84	38.87	1.69	13.13	55.95	11.14
61	23.60	28.82	24.14	21.29	28.32	26.06	4.37	37.29	5.01	19.81	7.82	6.90	0.40	7.51	10.36	11.06	4.42	7.92	3.49	7.46	0.75	9.64	24.49	50.00
62	1.33	1.23	26.54	5.86	8.36	1.74		1.34	0.29	7.71		0.20		0.69	1.46	1.47	0.29	2.50	0.23	0.02		5.42	5.16	0.97
63																							2.01	2.48
64	0.51	0.97	0.81	0.97	0.88	0.66	7.06	2.63	0.91	1.15	0.91	0.42	0.80	1.32	0.83	0.78	2.27	5.21	0.14	0.14	0.65	4.63	2.32	0.96
65	21.76	14.58	51.44	30.42	59.54	9.42	14.81	23.96	33.04	38.63	36.32	48.44	6.05	22.55	21.69	24.04	29.22	23.30	19.77	11.65	6.99	30.52	30.71	33.02
66	0.32	0.36	0.71	0.11	1.31	0.99	0.16	0.42	0.11	1.31	0.51	0.68	0.08	0.23	0.27	0.23	0.23	0.37	0.02	0.03	0.11	0.32	0.52	0.37
67	0.81	1.05	1.13	1.15	1.44	1.02	1.38	1.77	1.29	1.05	2.58	1.95		1.28	1.29	1.65	0.58	1.30				0.67	0.64	1.02
68	0.64		0.35		3.31	0.24	1.05	0.75	0.90	0.81	7.99	8.21		0.59	0.36	0.59	1.55	0.67	2.30	2.19		0.37	1.35	
69																								
70	0.02	0.03	0.03	0.03	0.03	0.02	0.04	0.04	0.03	0.02	0.05	0.04		0.03	0.03	0.03	0.02	0.03				0.02	0.02	0.02
71	1.00	1.04	1.04	1.04	1.06	0.98	1.10	1.09	1.05	1.03	1.08	1.08	0.78	1.00	1.03	1.07	1.00	1.06	5.43	0.52	0.57	8.92	0.91	1.03
72	34.03	24.80	35.78	22.41	29.74	40.33	23.76	36.14	36.89	41.47	49.19	43.44	15.97	43.17	34.22	30.34	41.83	26.30	34.87	43.12	2.81	19.49	28.35	26.16
73	6.58	16.50	7.50	7.65	9.93	11.69	9.71	9.73	6.34	6.54	6.12	6.67	25.79	7.60	5.76	5.97	7.57	6.11	7.22	12.38	3.33	6.97	9.39	7.30
74	3.03	1.90	3.56	2.02	3.44	1.80	12.77	3.04	2.18	3.15	2.14	2.74	2.82	2.79	3.05	1.62	4.09	3.01	2.03	3.12	4.17	2.70	4.52	2.25
75	8.51	7.66	8.84	7.29	14.25	9.49	44.65	15.76	4.72	14.19	5.22	5.91	86.69	8.22	23.82	9.34	14.88	4.58	1.78	34.36	3.18	12.69	13.41	8.55
76	4.28	31.08	3.92	98.96	8.05	27.06	36.63	7.42	9.61	4.49	9.47	6.88	34.01	7.74	10.52	4.63	12.00	3.16	11.18	77.58	10.35	5.80	10.30	12.56
77	3.39	1.17	6.69	0.83	0.46	1.31	3.51	0.45	3.57	4.37	0.09	1.95	0.29	0.18	0.95	0.65	0.38	0.09	8.95	16.32	1.27	6.26	0.51	0.68
78	0.54		0.89					0.93		0.21						0.19						2.84	2.12	
79	0.40	0.23	0.45	0.27	0.62	0.24	3.11	0.79	0.62	0.51	0.44	0.39	0.42	0.46	0.73	0.46	0.93	0.31	0.03	0.09	0.07	0.09	0.91	0.49
80	5.16	5.26	4.44	6.15	9.51	5.17	22.66	9.46	6.57	6.07	8.66	7.62	1.08	4.73	8.69	4.03	12.51	3.75	0.67	1.16	0.78	2.03	16.60	10.73
81		0.58	29.96	0.63	1.41	2.69		10.91		17.83		0.33		14.06	0.43							0.15	0.26	1.63
	1.48				1.53		0.14					0.06		18.77	34.42	7.96	4.48	4.54	0.50	10.38	0.06		3.44	
	353.59	459.67	401.24	552.73	489.67	616.94	473.63	570.54	374.50	383.77	367.97	342.59	492.59	280.79	436.84	261.20	364.67	325.53	345.86	515.15	446.46	398.35	397.11	612.39

Row	60 PETROLEUM REFINING AND RELATED INDUSTRIES	61 ELECTRICITY, GAS AND WATER	62 COAL MINING	63 CRUDE PETROLEUM AND NATURAL GAS	64 FEDERAL GOVERNMENT ENTERPRISES	65 TRANSPORTATION AND WAREHOUSING	66 STATE AND LOCAL GOVERNMENT ENTERPRISES	67 HOTELS, PERSONAL AND REPAIR SERVICES, EXCEPT AUTOMOBILE	68 AUTOMOBILE REPAIR AND SERVICES	69 RADIO AND TELEVISION BROADCASTING	70 AMUSEMENTS	71 MEDICAL AND EDUCATIONAL SERVICES, NONPROFIT ORGANIZATIONS	72 WHOLESALE AND RETAIL TRADE	73 FINANCE AND INSURANCE	74 COMMUNICATIONS, EXCEPT RADIO AND TELEVISION BROADCASTING	75 BUSINESS SERVICES	76 REAL ESTATE AND RENTAL	77 MAINTENANCE AND REPAIR CONSTRUCTION	78 RESEARCH AND DEVELOPMENT	79 OFFICE SUPPLIES	80 BUSINESS TRAVEL, ENTERTAINMENT AND GIFTS	81 SCRAP, USED AND SECONDHAND GOODS
	ENERGY				SERVICES																	
1		0.01			0.18	0.01		0.56	0.01	0.03	1.74	0.11	0.19	0.04	0.03	0.02	0.07				3.93	1.44
2								0.28					0.14				0.02	0.98				
3								0.91					0.13				0.05					
4		0.01										0.01	0.03				0.03				22.02	2.12
5	0.17					0.13	0.35	7.94	0.14			1.68	0.55	0.01		0.18	0.42		0.27		1.01	8.36
6	0.08				0.49	0.45		10.66	2.32	1.66	0.97	1.51	0.41	1.18	0.55	0.89	0.05	0.04	0.48			2.13
7	2.86	0.03		0.08		0.35	0.60	14.54	1.18	0.03	0.17	25.91	1.26	0.42	0.10	1.14	0.43		4.33		4.89	
8	0.63	0.02			63.19	3.01	0.11	1.08				7.47	5.56				1.01		0.75		304.28	0.99
9				0.93				0.05					0.29				0.18		0			27.76
10		0.01											0.09				0.06		198.28		0.70	
11						4.91							0.71				0.21		289.96			25.08
12		0.06	4.18			9.10		0.74	1.20		0.17	0.86	0.13	0.36	0.51	0.75	0.11		1.07			4.09
13	0.26	0.19				0.53		0.82		22.65		0.48	0.67		12.44		0.18	1.28	69.86		5.67	79.02
14			3.99			0.42							0.14				0.07	0.49	0.56			3.24
15	0.41	0.31	1.43	0.05		1.44	0.07	21.21	0.23	5.79	15.44	1.41	1.16	0.85	0.97	10.13	0.23	2.87	1.95	149.55	6.47	24.23
16	0.02	0.01	0.02					8.68			4.39	3.18	0.38			7.85	0.08		5.85	7.85	1.84	0.59
17						0.06		3.28					0.37			3.52	0.21	1.29	1.97			9.65
18								9.69					0.25				0.17	3.54	28.09		3.83	
19	0.06		0.05	0.06		0.78		5.75	2.03			11.44	0.44		0.01		0.13	0.94	20.33		1.11	37.55
20		0.39				0.07						0.13	0.46	0.18		19.85	0.13		2.25	4.75		12.10
21		0.01											0.19			5.55	0.10		2.25			8.
22		0.09		1.53		2.44							0.12			4.19	0.07	0.02	9.09			2.86
23			36.29	4.08									0.29			0.73	0.12	1.26	0.71			9.51
24	0.02	0.02	0.10	0.12	0.12	2.20	0.20	0.30	14.89			0.51	0.52	0.07	0.48	0.19	0.05	0.29	4.31			6.24
25	0.15	0.11	3.55	0.01		0.70			0.12				0.15		0.01	0.75	0.55	0.01	19.28			9.
26	0.01	0.04	2.06	0.93	2.28	2.64	2.57		142.97			0.08	2.18			0.21	0.30	0.01	34.46			121.85
27	0.07		1	8.30		0.43							0.31				0.14	1.11	0.56			15.95
28	0.03	0.12	1.51	0.07	0.05	0.21	0.06	0.61	4.19				0.19				0.05	7.29	13.48			
29	0.18	0.49	2.07	3.42		0.93		0.54	0.77				0.25		0.04		0.11	4.67	31.65			7.08
30				1.18		0.75		18.13					0.10		0.57		0.22	0.01	26.41			
31	0.15		0.38	0.64		0.02							1.02				0.15	32.23	2.81			29.01
32	0.02		0.20	0.07	0.18	0.21	0.22		13.26			0.01	0.23			0.02	0.14	0.02	0.41			32.61
33	7.02												0.08				0.04		0.19			9.82
34	0.12		5.71	0.58		0.46						0.89	0.46				0.08	1.24	0.56			
35	10.87	7.80	5.10	5.20	0.72	1.23	4.49	2.29	14.35			0.02	0.66		0.31	0.03	0.11	3.09	3.37	3.07	0.55	23.53
36	0.11	0.42	6.03	0.74		1.46		0.52					0.16		2.46	0.64	0.18	16.68	2.43			73.01
37		0.14															0.08					
38	0.08	2.91	8.27	0.30		1.13	0.47						0.08				0.33	16.22	0.94	1.76		145.14
39	0.15				0.43												0.08					
40	1.99	1.18	2.29	0.41	2.87	0.12	0.13	4.25	4.96				1.26			0.01	0.32	32.47			0.29	
41	3.46	0.01	0.51		0.10	0.04							0.04				0.13	7.77				
42	0.04	0.25	0.27	0.09	9.20	2.26	2.51	0.53	1.29	6.30	3.53	14.20	2.47	14.88	11.86	223.31	0.92	0.07	0.09	577.34	0.96	47.44
43	0.13			0.04		0.16		0.26	12.26			0.28	1.11				0.09	4.83	0.19	0.45	0.34	
44	1.87	0.02	0.54	0.06	1.58	0.25		1.55	0.12	1.28	0.14	0.89	3.70	0.92		0.33	0.15		0.30			25.39
45	3.32	0.80	2.31	0.48	6.60	1.01	0.40	11.96	0.41	5.35	0.60	3.73	4.82	3.84		2.69	0.17	4.04	1.27	241.55	0.48	
46	0.01					0.52							0.96				0.03					
47	0.13	0.13	6.84	0.59		0.27	0.01	0.41				0.14	0.61		0.02		0.38	24.76			0.26	
48						0.04											0.02				2.38	
49				0.22		0.47	0.45	1.91	2.05	1.13	0.57	1.00	0.25	0.80	0.38	0.57	0.09	0.06	0.51			
50	0.39	0.42	8.27	3.22	0.26	7.73	1.14	5.66	34.36	0.55	0.31	2.83	2.49	2.01	0.67	2.68	0.71	3.91	5.46	6.66	0.27	4.74
51		0.09	0.67			0.20		10.28				0.11	0.10		0.07		0.26		0.19			73.82
52	0.34		0.32	0.51		1.19	0.02	0.01	7.73				0.24				0.17	52.11				
53						0.10							0.02				0.01					
54					0.42	0.05					1.93	0.20					14.41				4.24	
55					151.43	1.03						0.23					21.88				10.22	
56							0.12				0.55		1.61				0.09					
57	0.86	0.10					0.01						0.04				0.17		1.50			
58	30.15	0.48	15.95	5.04		1.07	4.97	8.06	0.01			0.20	1.06		0.03	0.56	1.21	4.19	15.73	7.02		
59	0.06		0.02			0.03											0.02					
60	71.63	12.09	11.01	5.37	1.50	45.81	8.44	11.81	3.44	1.30	0.66	3.09	7.64	3.53	1.75	4.44	5.86	22.22	3.58			9.52
61	15.13	166.89	23.64	8.11	17.73	4.42	78.65	19.30	19.12	4.05	7.53	18.40	20.12	4.73	6.13	10.07	4.02	1.48				
62	0.55	26.94	171.35	0.02	11.40	0.80	16.57		1.33			0.01	0.04	0.23		1.23	0.17					
63	535.72	57.57		24.98			4.17										1.95		0.09			
64	1.82	19.38	1.00		1.54	1.67	0.85	0.58	0.45	0.59	0.56	0.70	10.29	12.34	4.14	26.88	4.38					
65	48.77	18.36	7.49	8.66	178.17	63.28	14.35	7.40	9.39	1.65	4.01	5.28	4.16	8.88	1.77	4.61	6.28	17.86	0.38		399.43	61.09
66	0.38	126.06	0.22	0.45	0.21	22.18	0.10	1.53	2.73	0.09	0.22	0.54	3.76	2.66	0.41	0.30	6.72	0.13				
67			0.24	0.04			1.55	29.08				4.85	2.36			4.97	4.22				145.39	
68	1.08	1.22	0.36	1.50	8.66	24.65	1.01	9.49	16.83	1.09		2.15	8.67	3.14	1.63	4.80	1.85	1.33				
69										2.68						62.23	0.23					
70			0.01			0.75				194.13	236.40	3.67	1.00	0.10	0.31	1.35	1.58		0.94		18.33	
71	0.94	0.81	0.98	0.97		0.94	0.05	0.96	0.96	0.97	0.96	13.04	1.00	5.31	0.93	0.15	0.61	0.57	100.86		5.64	
72	9.86	11.85	34.64	10.50	15.09	30.16	8.80	42.69	84.85	11.77	12.54	18.50	16.61	9.67	5.27	17.26	17.25	81.70	2.18		55.45	
73	6.57	5.46	9.1	11.19	1.24	21.08	9.41	16.24	26.18	8.12	23.07	11.65	16.59	203.65	5.66	12.02	33.34	2.92	0.94			
74	1.36	2.30	0.72	0.25	2.76	8.15	5.23	5.30	6.98	39.59	5.53	8.38	10.63	15.56	8.93	25.64	3.59	1.07	0.37			
75	20.28	11.12	4.95	35.46	13.55	14.95	14.25	25.89	19.45	40.18	37.92	25.22	49.92	38.73	17.53	22.43	20.62	3.56	3.75			
76	7.97	2.75	22.03	144.47	9.91	30.73	14.87	46.42	39.19	50.34	50.79	68.58	53.00	77.80	16.41	36.63	20.47	2.07	2.18			
77	1.47	27.20	0.88	0.44	3.45	37.51	249.17	2.88	13.68	5.17	22.42	29.97	8.14	4.52	31.53	0.90	95.29	0.06				
78	0.40				0.32							1.76										
79	0.29	0.81	0.22	0.30	5.06	1.30	6.02	1.59	0.40	1.11	1.21	3.84	2.25	5.15	3.89	10.09	0.44	0.14				
80	1.77	2.97	3.98	7.02	8.80	4.38	3.11	12.47	3.70	19.73	15.22	19.55	16.80	13.88	4.87	8.75	0.91	2.22	3.11			
81	0.18		1.94	11.39				3.79	9.18				1.10					0.72				
					44.89	15.98					18.61	0.22	0.32	4.05	5.80							
	208.07	489.51	583.74	68.92	435.62	518.82	544.30	608.13	481.29	572.67	531.85	681.06	724.47	560.44	851.53	458.67	722.25	612.34	76.80			

other sectors. Reading vertically down one sector, they govern inputs, or purchases. The coefficients are ratios of the input in a given cell to the total output of sector in whose vertical column the cell appears. Cells are colored where the ratio exceeds 1/81.

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
		FINAL NONMETAL								FINAL METAL																						BASIC METAL			
		FOOTWEAR AND OTHER LEATHER PRODUCTS	MISCELLANEOUS FURNITURE AND FIXTURES	HOUSEHOLD FURNITURE	TOBACCO MANUFACTURES	APPAREL	MISCELLANEOUS FABRICATED TEXTILE PRODUCTS	DRUGS, CLEANING AND TOILET PREPARATIONS	FOOD AND KINDRED PRODUCTS	SPECIAL-INDUSTRY MACHINERY AND EQUIPMENT	ORDNANCE AND ACCESSORIES	AIRCRAFT AND PARTS	MISCELLANEOUS TRANSPORTATION EQUIPMENT	RADIO, TELEVISION AND COMMUNICATION EQUIPMENT	MATERIALS-HANDLING MACHINERY AND EQUIPMENT	MISCELLANEOUS MANUFACTURING	OPTICAL, OPHTHALMIC AND PHOTOGRAPHIC EQUIPMENT	SERVICE-INDUSTRY MACHINES	HOUSEHOLD APPLIANCES	SCIENTIFIC AND CONTROLLING INSTRUMENTS	OFFICE, COMPUTING AND ACCOUNTING MACHINES	FARM MACHINERY AND EQUIPMENT	ENGINES AND TURBINES	CONSTRUCTION, MINING AND OIL FIELD MACHINERY	MISCELLANEOUS ELECTRICAL MACHINERY, EQUIPMENT AND SUPPLIES	METALWORKING MACHINERY AND EQUIPMENT	MOTOR VEHICLES AND EQUIPMENT	GENERAL INDUSTRIAL MACHINERY AND EQUIPMENT	ELECTRIC LIGHTING AND WIRING EQUIPMENT	ELECTRIC INDUSTRIAL EQUIPMENT AND APPARATUS	ELECTRONIC COMPONENTS AND ACCESSORIES	HEATING, PLUMBING AND STRUCTURAL METAL PRODUCTS	MACHINE SHOP PRODUCTS	METAL CONTAINERS	STAMPINGS, SCREW-MACHINE PRODUCTS AND BOLTS
FINAL NONMETAL	FOOTWEAR AND OTHER LEATHER PRODUCTS 1	1.0920	.0004	.0007	.0001	.0014	.0035	.0002	.0002	.0003	.0005	.0002	.0003	.0003	.0005	.0074	.0008	.0004	.0017	.0014	.0003	.0003	.0003	.0002	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0003	.0017	.0002	.0006
	MISCELLANEOUS FURNITURE AND FIXTURES 2	.0001	1.0207	.0080	.0001	.0001	.0030	.0001	.0001	.0002	.0007	.0024	.0050	.0004	.0007	.0012	.0002	.0010	.0006	.0042	.0004	.0008	.0002	.0002	.0001	.0002	.0005	.0004	.0001	.0002	.0002	.0019	.0001	.0001	.0003
	HOUSEHOLD FURNITURE 3	.0006	.0299	1.0161	.0001	.0002	.0038	.0002	.0002	.0006	.0014	.0013	.0080	.0269	.0004	.0007	.0003	.0017	.0006	.0016	.0007	.0004	.0003	.0005	.0004	.0003	.0007	.0008	.0004	.0007	.0071	.0015	.0002	.0003	.0006
	TOBACCO MANUFACTURES 4	.0004	.0006	.0005	1.2370	.0005	.0005	.0005	.0004	.0007	.0009	.0004	.0006	.0009	.0007	.0008	.0005	.0007	.0006	.0010	.0009	.0006	.0006	.0006	.0007	.0006	.0005	.0007	.0006	.0009	.0009	.0006	.0005	.0004	.0006
	APPAREL 5	.0084	.0025	.0018	.0003	1.2098	.0139	.0012	.0014	.0023	.0021	.0022	.0026	.0021	.0022	.0032	.0018	.0022	.0021	.0046	.0019	.0022	.0020	.0020	.0023	.0023	.0021	.0023	.0022	.0021	.0026	.0023	.0024	.0013	.0023
	MISCELLANEOUS FABRICATED TEXTILE PRODUCTS 6	.0022	.0020	.0026	.0009	.0188	1.0708	.0018	.0031	.0006	.0006	.0005	.0013	.0006	.0008	.0025	.0008	.0009	.0008	.0013	.0005	.0008	.0008	.0007	.0011	.0010	.0109	.0006	.0006	.0006	.0006	.0010	.0005	.0007	.0010
	DRUGS, CLEANING AND TOILET PREPARATIONS 7	.0101	.0024	.0028	.0031	.0039	.0060	1.0716	.0063	.0026	.0026	.0019	.0030	.0021	.0028	.0062	.0027	.0030	.0025	.0041	.0016	.0028	.0024	.0024	.0025	.0020	.0034	.0023	.0025	.0020	.0020	.0025	.0023	.0053	.0030
	FOOD AND KINDRED PRODUCTS 8	.0918	.0127	.0239	.0177	.0148	.0184	.0522	1.2564	.0126	.0147	.0072	.0117	.0151	.0126	.0184	.0114	.0125	.0121	.0206	.0149	.0111	.0101	.0102	.0126	.0097	.0098	.0116	.0119	.0145	.0148	.0099	.0091	.0089	.0101
FINAL METAL	SPECIAL-INDUSTRY MACHINERY AND EQUIPMENT 9	.0015	.0022	.0053	.0008	.0044	.0065	.0044	.0008	1.0547	.0033	.0020	.0024	.0017	.0072	.0024	.0033	.0050	.0020	.0035	.0072	.0056	.0034	.0043	.0018	.0108	.0023	.0094	.0015	.0026	.0017	.0060	.0084	.0025	.0024
	ORDNANCE AND ACCESSORIES 10	.0003	.0007	.0003	.0001	.0002	.0005	.0005	.0002	.0021	1.0347	.0684	.0011	.0301	.0009	.0007	.0027	.0018	.0017	.0345	.0030	.0038	.0027	.0011	.0010	.0012	.0015	.0022	.0007	.0030	.0110	.0012	.0007	.0008	.0014
	AIRCRAFT AND PARTS 11	.0012	.0030	.0014	.0006	.0009	.0019	.0014	.0011	.0082	.2671	1.2551	.0091	.0204	.0064	.0025	.0026	.0113	.0034	.0317	.0112	.0079	.0192	.0047	.0032	.0096	.0036	.0249	.0016	.0043	.0047	.0047	.0059	.0066	.0040
	MISCELLANEOUS TRANSPORTATION EQUIPMENT 12	.0008	.0023	.0017	.0006	.0010	.0010	.0010	.0012	.0056	.0056	.0016	1.0750	.0014	.0072	.0035	.0015	.0029	.0039	.0030	.0010	.0049	.0127	.0078	.0015	.0019	.0029	.0079	.0013	.0072	.0011	.0091	.0048	.0021	.0019
	RADIO, TELEVISION AND COMMUNICATION EQUIPMENT 13	.0009	.0031	.0015	.0006	.0008	.0013	.0013	.0008	.0132	.0481	.0408	.0046	1.0723	.0032	.0045	.0068	.0068	.0033	.0177	.0147	.0030	.0037	.0031	.0079	.0027	.0101	.0057	.0047	.0146	.0409	.0031	.0026	.0027	.0026
	MATERIALS-HANDLING MACHINERY AND EQUIPMENT 14	.0002	.0005	.0011	.0001	.0002	.0003	.0003	.0002	.0063	.0006	.0010	.0055	.0003	1.0405	.0003	.0003	.0019	.0006	.0004	.0003	.0016	.0025	.0071	.0005	.0033	.0009	.0092	.0004	.0009	.0003	.0017	.0009	.0006	.0008
	MISCELLANEOUS MANUFACTURING 15	.0074	.0195	.0085	.0033	.0265	.0237	.0052	.0027	.0039	.0063	.0048	.0060	.0052	.0332	1.0615	.0048	.0051	.0056	.0093	.0041	.0045	.0043	.0035	.0039	.0052	.0050	.0034	.0084	.0033	.0045	.0042	.0026	.0037	.0082
	OPTICAL, OPHTHALMIC AND PHOTOGRAPHIC EQUIPMENT 16	.0020	.0007	.0008	.0009	.0008	.0010	.0022	.0008	.0029	.0023	.0035	.0009	.0037	.0009	.0010	1.0600	.0011	.0032	.0072	.0010	.0010	.0008	.0008	.0013	.0008	.0011	.0011	.0009	.0015	.0012	.0009	.0007	.0007	.0012
	SERVICE-INDUSTRY MACHINES 17	.0004	.0108	.0008	.0004	.0003	.0005	.0012	.0004	.0067	.0053	.0019	.0043	.0015	.0037	.0010	.0006	1.0526	.0322	.0027	.0006	.0021	.0013	.0022	.0010	.0033	.0029	.0108	.0016	.0011	.0006	.0100	.0014	.0009	.0027
	HOUSEHOLD APPLIANCES 18	.0004	.0020	.0018	.0002	.0004	.0004	.0006	.0004	.0024	.0019	.0035	.0068	.0013	.0011	.0028	.0005	.0687	1.0138	.0018	.0006	.0047	.0011	.0011	.0034	.0029	.0010	.0015	.0011	.0014	.0015	.0083	.0007	.0031	.0033
	SCIENTIFIC AND CONTROLLING INSTRUMENTS 19	.0028	.0081	.0012	.0004	.0008	.0044	.0052	.0006	.0048	.0313	.0240	.0047	.0098	.0038	.0028	.0170	.0198	.0353	1.0647	.0058	.0042	.0038	.0032	.0067	.0034	.0086	.0101	.0049	.0166	.0075	.0121	.0029	.0022	.0039
	OFFICE, COMPUTING AND ACCOUNTING MACHINES 20	.0014	.0034	.0012	.0018	.0010	.0012	.0044	.0014	.0029	.0026	.0018	.0012	.0038	.0025	.0044	.0028	.0016	.0033	.0166	1.0969	.0016	.0011	.0015	.0021	.0010	.0017	.0013	.0011	.0020	.0066	.0017	.0016	.0012	.0017
	FARM MACHINERY AND EQUIPMENT 21	.0008	.0015	.0009	.0027	.0010	.0014	.0014	.0023	.0043	.0020	.0009	.0075	.0067	.0075	.0011	.0007	.0016	.0014	.0011	.0006	1.0417	.0174	.0211	.0016	.0027	.0028	.0038	.0011	.0012	.0006	.0033	.0016	.0016	.0022
	ENGINES AND TURBINES 22	.0006	.0010	.0008	.0007	.0005	.0007	.0014	.0008	.0040	.0039	.0035	.0390	.0014	.0217	.0010	.0011	.0052	.0027	.0020	.0013	.0596	1.1056	.0341	.0034	.0046	.0076	.0183	.0016	.0201	.0014	.0088	.0073	.0014	.0031
	CONSTRUCTION, MINING AND OIL FIELD MACHINERY 23	.0006	.0020	.0012	.0005	.0006	.0008	.0012	.0007	.0113	.0025	.0018	.0099	.0014	.0583	.0013	.0015	.0031	.0025	.0022	.0010	.0188	.0353	1.0636	.0038	.0044	.0031	.0117	.0021	.0037	.0021	.0066	.0058	.0036	.0030
	MISCELLANEOUS ELECTRICAL MACHINERY, EQUIPMENT AND SUPPLIES 24	.0005	.0010	.0009	.0006	.0005	.0007	.0006	.0010	.0021	.0035	.0061	.0038	.0020	.0046	.0014	.0049	.0024	.0021	.0029	.0015	.0112	.0226	.0039	1.0426	.0025	.0243	.0030	.0329	.0048	.0023	.0020	.0038	.0011	.0025
	METALWORKING MACHINERY AND EQUIPMENT 25	.0016	.0072	.0049	.0008	.0011	.0019	.0023	.0018	.0327	.0245	.0314	.0133	.0107	.0270	.0043	.0077	.0117	.0152	.0197	.0143	.0284	.0280	.0267	.0217	1.0672	.0237	.0273	.0113	.0184	.0107	.0138	.0256	.0202	.0189
	MOTOR VEHICLES AND EQUIPMENT 26	.0025	.0092	.0047	.0022	.0022	.0036	.0032	.0049	.0129	.0157	.0189	.0297	.0054	.0245	.0064	.0039	.0271	.0122	.0281	.0043	.0373	.0512	.0322	.0576	.0780	1.4336	.0188	.0075	.0092	.0050	.0157	.0129	.0097	.0459
	GENERAL INDUSTRIAL MACHINERY AND EQUIPMENT 27	.0012	.0050	.0030	.0008	.0011	.0022	.0018	.0013	.0683	.0150	.0187	.0250	.0045	.0851	.0034	.0021	.0236	.0165	.0108	.0102	.0721	.0464	.0724	.0228	.0417	.0135	1.0812	.0053	.0142	.0039	.0183	.0155	.0122	.0053
	ELECTRIC LIGHTING AND WIRING EQUIPMENT 28	.0018	.0025	.0024	.0005	.0007	.0011	.0008	.0012	.0034	.0162	.0050	.0065	.0167	.0060	.0051	.0060	.0118	.0114	.0071	.0067	.0032	.0038	.0031	.0437	.0031	.0090	.0041	1.0456	.0212	.0118	.0048	.0029	.0020	.0064
	ELECTRIC INDUSTRIAL EQUIPMENT AND APPARATUS 29	.0014	.0048	.0027	.0008	.0013	.0019	.0021	.0014	.0531	.0333	.0129	.0460	.0307	.0652	.0096	.0182	.1098	.0545	.0460	.0325	.0174	.0291	.0225	.0338	.0374	.0097	.0666	.0428	1.0799	.0425	.0204	.0107	.0073	.0099
	ELECTRONIC COMPONENTS AND ACCESSORIES 30	.0014	.0017	.0012	.0004	.0006	.0009	.0010	.0005	.0078	.0143	.0176	.0031	.2088	.0039	.0041	.0031	.0059	.0040	.0391	.0531	.0019	.0027	.0021	.0184	.0024	.0046	.0044	.0071	.0356	1.0752	.0032	.0015	.0012	.0025
BASIC METAL	HEATING, PLUMBING AND STRUCTURAL METAL PRODUCTS 31	.0012	.0160	.0057	.0009	.0011	.0016	.0015	.0019	.0160	.0050	.0033	.0539	.0028	.0185	.0026	.0014	.0295	.0203	.0038	.0017	.0075	.0059	.0215	.0026	.0075	.0051	.0238	.0047	.0057	.0025	1.0237	.0049	.0090	.0114
	MACHINE SHOP PRODUCTS 32	.0010	.0029	.0019	.0005	.0006	.0011	.0012	.0011	.0086	.0941	.0211	.0096	.0057	.0228	.0045	.0023	.0052	.0048	.0140	.0048	.0236	.0405	.0110	.0123	.0107	.0139	.0112	.0047	.0056	.0040	.0101	1.0755	.0117	.0088
	METAL CONTAINERS 33	.0031	.0019	.0024	.0028	.0012	.0017	.0208	.0310	.0009	.0010	.0008	.0014	.0010	.0011	.0019	.0014	.0015	.0015	.0037	.0008	.0012	.0010	.0010	.0012	.0011	.0014	.0009	.0014	.0011	.0011	.0016	.0007	1.0034	.0048
	STAMPINGS, SCREW-MACHINE PRODUCTS AND BOLTS 34	.0029	.0138	.0102	.0012	.0016	.0027	.0062	.0058	.0223	.0207	.0323	.0157	.0306	.0292	.0192	.0103	.0514	.0648	.0278	.0177	.0451	.0149	.0208	.0356	.0375	.0532	.0215	.0358	.0240	.0314	.0299	.0120	.0222	1.0367
	OTHER FABRICATED METAL PRODUCTS 35	.0132	.0498	.0715	.0046	.0051	.0081	.0147	.0061	.0302	.0254	.0233	.0377	.0246	.0376	.0268	.0169	.0445	.0479	.0281	.0130	.0222	.0170	.0276	.0177	.0347	.0647	.0333	.0279	.0190	.0229	.0483	.0323	.0210	.0417
	PRIMARY NONFERROUS METAL MANUFACTURING 36	.0070	.0403	.0288	.0056	.0063	.0088	.0115	.0069	.0985	.1180	.0798	.0628	.0648	.0562	.0868	.0566	.1218	.0908	.0908	.0482	.0458	.0857	.0403	.1885	.0717	.0559	.0768	.1059	.1359	.0911	.1404	.1401	.0436	.1229
	NONFERROUS METAL ORES MINING 37	.0012	.0054	.0038	.0009	.0011	.0016	.0027	.0011	.0120	.0138	.0095	.0083	.0077	.0074	.0104	.0072	.0146	.0121	.0113	.0058	.0065	.0107	.0058	.0235	.0089	.0075	.0096	.0147	.0160	.0108	.0175	.0165	.0077	.0153
	PRIMARY IRON AND STEEL MANUFACTURING 38	.0109	.1544	.0630	.0069	.0083	.0130	.0268	.0257	.1696	.0718	.0868	.2233	.0472	.2154	.0613	.0270	.1598	.1565	.0661	.0530	.2595	.2000	.2627	.0837	.1524	.2088	.1961	.1235	.1127	.0568	.3560	.1403	.5900	.3007
	IRON AND FERROALLOY ORES MINING 39	.0010	.0095	.0041	.0006	.0008	.0012	.0026	.0017	.0107	.0049	.0056	.0138	.0032	.0133	.0043	.0024	.0103	.0108	.0045	.0035	.0159	.0125	.0160	.0076	.0097	.0129	.0122	.0081	.0082	.0040	.0220	.0091	.0356	.0186
BASIC NONMETAL	STONE AND CLAY PRODUCTS 40	.0081	.0097	.0066	.0019	.0021	.0032	.0062	.0034	.0130	.0116	.0109	.0191	.0101	.0141	.0080	.0269	.0161	.0169	.0101	.0073	.0166	.0169	.0160	.0179	.0156	.0133	.0193	.0152	.0151	.0143	.0181	.0273	.0162	.0183
	STONE AND CLAY MINING AND QUARRYING 41	.0012	.0020	.0015	.0013	.0008	.0012	.0023	.0016	.0019	.0014	.0013	.0025	.0013	.0021	.0016	.0027	.0021	.0021	.0014	.0010	.0028	.0022	.0025	.0022	.0019	.0022	.0049	.0022	.0019	.0020	.0029	.0026	.0033	.0026
	PRINTING AND PUBLISHING 42	.0254	.0143	.0163	.0254	.0145	.0169	.0584	.0209	.0137	.0149	.0095	.0135	.0171	.0153	.0242	.0248	.0151	.0341	.0142	.0190	.0185	.0142	.0135	.0157	.0111	.0202	.0132	.0133	.0129	.0124	.0140	.0105	.0169	.0137
	GLASS AND GLASS PRODUCTS 43	.0025	.0419	.0173	.0007	.0022	.0035	.0241	.0135	.0016	.0035	.0022	.0079	.0140	.0021	.0078	.0137	.0053	.0040	.0068	.0031	.0018	.0022	.0015	.0045	.0019	.0172	.0015	.0332	.0038	.0375	.0054	.0010	.0012	.0027
	PAPERBOARD CONTAINERS AND BOXES 44	.0204	.0288	.0273	.0180	.0165	.0237	.0413	.0223	.0041	.0082	.0045	.0058	.0124	.0058	.0488	.0134	.0152	.0159	.0138	.0054	.0070	.0091	.0046	.0128	.0036	.0079	.0057	.0262	.0087	.0134	.0087	.0026	.0182	.0139
	PAPER AND ALLIED PRODUCTS, EXCEPT CONTAINERS 45	.0362	.0306	.0318	.0378	.0234	.0476	.0547	.0296	.0141	.0159	.0100	.0157	.0253	.0148	.0690	.0628	.0245	.0259	.0243	.0216	.0152	.0151	.0122	.0198	.0096	.0222	.0156	.0280	.0244	.0321	.0165	.0086	.0256	.0227
	WOODEN CONTAINERS 46	.0015	.0010	.0012	.0033	.0006	.0008	.0006	.0032	.0005	.0014	.0003	.0006	.0004	.0004	.0010	.0004	.0064	.0066	.0007	.0006	.0007	.0003	.0003	.0004	.0003	.0005	.0005	.0005	.0004	.0005	.0016	.0003	.0009	.0009
	LUMBER AND WOOD PRODUCTS, EXCEPT CONTAINERS 47	.0197	.0996	.1882	.0069	.0047	.0085	.0099	.0067	.0130	.0061	.0067	.0441	.0126	.0069	.0385	.0087	.0147	.0120	.0071	.0051	.0105	.0051	.0063	.0049	.0059	.0074	.0071	.0081	.0071	.0080	.0100	.0034	.0070	.0133
	FORESTRY AND FISHERY PRODUCTS 48	.0029	.0102	.0192	.0008	.0127	.0017	.0015	.0063	.0015	.0008	.0008	.0046	.0015	.0009	.0047	.0011	.0017	.0014	.0010	.0007	.0012	.0007	.0008	.0007	.0007	.0009	.0009	.0010	.0009	.0010	.0011	.0005	.0008	.0015
	MISCELLANEOUS TEXTILE GOODS AND FLOOR COVERINGS 49	.0239	.0225	.0223	.0014	.0243	.1101	.0022	.0020	.0022	.0035	.0024	.0033	.0025	.0032	.0131	.0021	.0026	.0042	.0050	.0017	.0041	.0021	.0024	.0053	.0017	.0118	.0015	.0025	.0020	.0017	.0015	.0011	.0023	.0021
	RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS 50	.0744	.0181	.0502	.0071	.0109	.0454	.0171	.0091	.0197	.0338	.0149	.0179	.0190	.0291	.0465	.0138	.0225	.0416	.0206	.0165	.0442	.0142	.0234	.0579	.0113	.0500	.0112	.0239	.0139	.0134	.0086	.0066	.0219	.0142
	BROAD AND NARROW FABRICS, YARN AND THREAD MILLS 51	.0587	.0172	.1006	.0026	.5300	.7675	.0044	.0047	.0067	.0055	.0043	.0075	.0068	.0085	.0407	.0050	.0058	.0103	.0195	.0034	.0066	.0048	.0050	.0076	.0043	.0202	.0053	.0048	.0047	.0046	.0060	.0037	.0054	.0054
	PAINTS AND ALLIED PRODUCTS 52	.0014	.0196	.0234	.0012	.0020	.0029	.0043	.0024	.0022	.0024	.0025	.0111	.0027	.0049	.0106	.0017	.0081	.0082	.0024	.0022	.0063	.0032	.0034	.0022	.0020	.0077	.0027	.0068	.0048	.0024	.0049	.0016	.0189	.0072
	LEATHER TANNING AND INDUSTRIAL LEATHER PRODUCTS 53	.2668	.0020	.0017	.0001	.0044	.0013	.0002	.0001	.0017	.0003	.0002	.0008	.0005	.0006	.0097	.0004	.0004	.0009	.0014	.0003	.0016	.0004	.0004	.0003	.0003	.0007	.0005	.0004	.0003	.0002	.0003	.0009	.0006	.0004
	LIVESTOCK AND LIVESTOCK PRODUCTS 54	.0515	.0076	.0148	.0295	.0204	.0293	.0182	.3709	.0056	.0064	.0034	.0056	.0063	.0058	.0105	.0050	.0057	.0062	.0085	.0059	.0060	.0044	.0047	.0065	.0043	.0059	.0048	.0053	.0058	.0061	.0043	.0040	.0043	.0045
	MISCELLANEOUS AGRICULTURAL PRODUCTS 55	.0315	.0115	.0279	.2502	.0735	.1023	.0136	.2032	.0059	.0059	.0038	.0072	.0066	.0061	.0149	.0056	.0062	.0070	.0101	.0055	.0064	.0046	.0047	.0062	.0046	.0073	.0051	.0054	.0058	.0064	.0050	.0043	.0047	.0052
	AGRICULTURAL, FORESTRY AND FISHERY SERVICES 56	.0023	.0010	.0020	.0102	.0035	.0047	.0010	.0150	.0005	.0005	.0003	.0007	.0005	.0005	.0010	.0004	.0006	.0006	.0007	.0005	.0019	.0004	.0004	.0005	.0004	.0005	.0004	.0005	.0005	.0005	.0004	.0004	.0004	.0004
	PLASTICS AND SYNTHETIC MATERIALS 57	.0239	.0152	.0274	.0256	.0687	.0995	.0117	.0041	.0081	.0104	.0070	.0165	.0163	.0102	.0429	.0083	.0111	.0155	.0123	.0071	.0112	.0070	.0073	.0222	.0056	.0169	.0059	.0291	.0151	.0151	.0067	.0047	.0097	.0115
	CHEMICALS AND SELECTED CHEMICAL PRODUCTS 58	.0491	.0256	.0347	.0333	.0549	.0749	.1855	.0278	.0178	.0190	.0137	.0251	.0210	.0175	.0482	.0958	.0285	.0292	.0213	.0116	.0207	.0147	.0159	.0522	.0129	.0273	.0159	.0346	.0235	.0330	.0213	.0120	.0257	.0243
	CHEMICAL AND FERTILIZER MINERAL MINING 59	.0021	.0011	.0014	.0015	.0020	.0028	.0061	.0014	.0008	.0008	.0006	.0011	.0008	.0008	.0019	.0033	.0012	.0012	.0009	.0005	.0009	.0007	.0008	.0020	.0006	.0012	.0007	.0014	.0010	.0013	.0010	.0006	.0012	.0011
ENERGY	PETROLEUM REFINING AND RELATED INDUSTRIES 60	.0130	.0146	.0169	.0180	.0151	.0211	.0310	.0257	.0168	.0131	.0107	.0179	.0105	.0155	.0171	.0162	.0159	.0138	.0111	.0087	.0170	.0154	.0160	.0140	.0145	.0157	.0149	.0134	.0136	.0118	.0192	.0203	.0192	.0195
	ELECTRICITY, GAS AND WATER 61	.0188	.0250	.0243	.0110	.0218	.0297	.0237	.0219	.0248	.0219	.0206	.0282	.0182	.0244	.0241	.0197	.0274	.0277	.0198	.0152	.0274	.0240	.0263	.0277	.0229	.0281	.0259	.0256	.0254	.0253	.0327	.0263	.0373	.0334
	COAL MINING 62	.0034	.0072	.0053	.0021	.0035	.0050	.0050	.0036	.0074	.0043	.0046	.0104	.0037	.0090	.0051	.0057	.0080	.0080	.0040	.0031	.0118	.0098	.0113	.0054	.0066	.0102	.0086	.0064	.0063	.0043	.0142	.0067	.0218	.0126
	CRUDE PETROLEUM AND NATURAL GAS 63	.0084	.0097	.0109	.0107	.0098	.0136	.0189	.0154	.0108	.0086	.0072	.0116	.0070	.0101	.0110	.0103	.0105	.0094	.0074	.0058	.0111	.0100	.0105	.0095	.0094	.0104	.0098	.0090	.0091	.0081	.0126	.0128	.0129	.0128
SERVICES	FEDERAL GOVERNMENT ENTERPRISES 64	.0077	.0049	.0048	.0064	.0063	.0068	.0104	.0048	.0047	.0047	.0039	.0049	.0068	.0055	.0065	.0068	.0057	.0083	.0049	.0052	.0065	.0046	.0045	.0066	.0041	.0070	.0048	.0056	.0060	.0072	.0050	.0044	.0049	.0048
	TRANSPORTATION AND WAREHOUSING 65	.0494	.0583	.0651	.0340	.0466	.0623	.0560	.0831	.0492	.0490	.0360	.0619	.0471	.0545	.0546	.0444	.0577	.0564	.0489	.0385	.0596	.0514	.0550	.0513	.0407	.0654	.0523	.0500	.0499	.0455	.0654	.0415	.0619	.0595
	STATE AND LOCAL GOVERNMENT ENTERPRISES 66	.0045	.0057	.0058	.0028	.0048	.0067	.0054	.0061	.0053	.0048	.0042	.0062	.0042	.0054	.0056	.0044	.0060	.0059	.0045	.0036	.0061	.0052	.0056	.0057	.0047	.0062	.0055	.0055	.0053	.0053	.0069	.0052	.0078	.0068
	HOTELS, PERSONAL AND REPAIR SERVICES, EXCEPT AUTOMOBILE 67	.0072	.0063	.0068	.0025	.0075	.0072	.0053	.0038	.0067	.0071	.0032	.0066	.0075	.0067	.0070	.0056	.0064	.0064	.0080	.0075	.0058	.0056	.0057	.0066	.0060	.0051	.0064	.0063	.0073	.0080	.0057	.0060	.0046	.0058
	AUTOMOBILE REPAIR AND SERVICES 68	.0041	.0062	.0071	.0032	.0037	.0058	.0049	.0103	.0047	.0030	.0023	.0049	.0032	.0042	.0054	.0036	.0050	.0041	.0032	.0028	.0047	.0033	.0041	.0037	.0033	.0042	.0040	.0036	.0034	.0030	.0057	.0039	.0044	.0041
	RADIO AND TELEVISION BROADCASTING 69	.0033	.0019	.0025	.0048	.0022	.0024	.0116	.0035	.0020	.0019	.0012	.0020	.0027	.0024	.0029	.0049	.0024	.0069	.0022	.0027	.0031	.0020	.0021	.0027	.0018	.0036	.0020	.0021	.0018	.0018	.0020	.0016	.0020	.0018
	AMUSEMENTS 70	.0016	.0014	.0016	.0017	.0014	.0016	.0040	.0017	.0015	.0016	.0009	.0014	.0018	.0016	.0018	.0021	.0016	.0028	.0018	.0018	.0017	.0013	.0014	.0017	.0013	.0017	.0014	.0015	.0015	.0016	.0014	.0012	.0012	.0013
	MEDICAL AND EDUCATIONAL SERVICES, NONPROFIT ORGANIZATIONS 71	.0029	.0024	.0026	.0027	.0030	.0032	.0024	.0043	.0024	.0027	.0023	.0027	.0025	.0025	.0025	.0023	.0026	.0025	.0024	.0020	.0026	.0030	.0024	.0024	.0022	.0029	.0024	.0024	.0024	.0024	.0026	.0022	.0027	.0025
	WHOLESALE AND RETAIL TRADE 72	.0657	.0936	.0977	.0420	.0823	.1076	.0608	.0878	.0762	.0697	.0504	.0913	.0768	.0863	.0988	.0639	.1004	.0838	.0748	.0775	.0829	.0659	.0737	.0740	.0603	.0808	.0833	.0983	.0652	.0885	.0787	.0604	.0839	.0675
	FINANCE AND INSURANCE 73	.0235	.0208	.0223	.0147	.0251	.0267	.0257	.0258	.0220	.0213	.0141	.0212	.0162	.0246	.0249	.0184	.0257	.0196	.0185	.0161	.0231	.0208	.0222	.0187	.0213	.0209	.0210	.0184	.0173	.0180	.0253	.0216	.0244	.0239
	COMMUNICATIONS, EXCEPT RADIO AND TELEVISION BROADCASTING 74	.0094	.0101	.0117	.0058	.0092	.0100	.0123	.0097	.0164	.0111	.0101	.0094	.0094	.0109	.0121	.0093	.0108	.0129	.0104	.0095	.0100	.0089	.0097	.0097	.0138	.0098	.0156	.0084	.0095	.0081	.0107	.0121	.0081	.0085
	BUSINESS SERVICES 75	.0526	.0310	.0406	.0761	.0349	.0382	.1860	.0558	.0318	.0311	.0193	.0312	.0431	.0379	.0470	.0784	.0383	.1100	.0351	.0431	.0503	.0318	.0339	.0433	.0282	.0872	.0313	.0331	.0286	.0288	.0326	.0262	.0314	.0290
	REAL ESTATE AND RENTAL 76	.0309	.0324	.0365	.0346	.0386	.0443	.0368	.0450	.0302	.0253	.0214	.0266	.0277	.0318	.0383	.0323	.0368	.0302	.0296	.0247	.0282	.0241	.0254	.0282	.0352	.0261	.0274	.0296	.0261	.0394	.0288	.0327	.0287	.0290
	MAINTENANCE AND REPAIR CONSTRUCTION 77	.0100	.0114	.0124	.0116	.0119	.0147	.0111	.0230	.0113	.0112	.0097	.0115	.0101	.0114	.0145	.0091	.0130	.0116	.0094	.0083	.0122	.0101	.0107	.0099	.0121	.0154	.0116	.0101	.0106	.0109	.0133	.0139	.0151	.0124
	RESEARCH AND DEVELOPMENT 78	.0002	.0003	.0003	.0002	.0004	.0006	.0005	.0002	.0003	.0005	.0014	.0006	.0007	.0005	.0004	.0017	.0004	.0004	.0003	.0002	.0007	.0064	.0005	.0004	.0003	.0012	.0004	.0004	.0004	.0011	.0008	.0003	.0007	.0005
	OFFICE SUPPLIES 79	.0026	.0023	.0023	.0015	.0022	.0024	.0035	.0020	.0024	.0027	.0020	.0024	.0027	.0026	.0028	.0024	.0025	.0029	.0029	.0028	.0025	.0021	.0022	.0023	.0021	.0022	.0024	.0021	.0025	.0025	.0020	.0019	.0018	.0021
	BUSINESS TRAVEL, ENTERTAINMENT AND GIFTS 80	.0158	.0199	.0187	.0070	.0162	.0188	.0190	.0132	.0246	.0321	.0142	.0217	.0318	.0254	.0230	.0196	.0238	.0221	.0347	.0336	.0200	.0207	.0207	.0247	.0205	.0163	.0240	.0227	.0312	.0308	.0188	.0187	.0134	.0190
	SCRAP, USED AND SECONDHAND GOODS 81	.0017	.0066	.0036	.0012	.0014	.0039	.0026	.0020	.0076	.0033	.0039	.0107	.0032	.0079	.0049	.0026	.0062	.0061	.0031	.0026	.0119	.0097	.0099	.0038	.0060	.0082	.0095	.0060	.0045	.0032	.0160	.0069	.0188	.0101
	NONCOMPETITIVE IMPORTS	.0089	.0036	.0059	.0045	.0088	.0135	.0065	.0340	.0055	.0034	.0022	.0030	.0033	.0038	.0220	.0028	.0033	.0040	.0036	.0025	.0039	.0025	.0028	.0046	.0060	.0044	.0026	.0031	.0041	.0051	.0027	.0021	.0033	.0028
	VALUE ADDED																																		
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34

INVERSE-COEFFICIENT TABLE shows indirect relations between the 81 sectors of the economy. Each sector delivers a certain amount of its output to what is called "final demand." (The final-demand totals appear in table on page 32.) The coefficient

BASIC NONMETAL — ENERGY — SERVICES

STONE AND CLAY PRODUCTS · STONE AND CLAY MINING AND QUARRYING · PRINTING AND PUBLISHING · PAPER AND ALLIED PRODUCTS · PAPERBOARD CONTAINERS AND BOXES · GLASS AND GLASS PRODUCTS · LUMBER AND WOOD PRODUCTS, EXCEPT CONTAINERS · WOODEN CONTAINERS · MISCELLANEOUS TEXTILE GOODS AND FLOOR COVERINGS · FORESTRY AND FISHERY PRODUCTS · BROAD AND NARROW FABRICS, YARN AND THREAD MILLS · RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS · LEATHER TANNING AND INDUSTRIAL LEATHER PRODUCTS · PAINTS AND ALLIED PRODUCTS · LIVESTOCK AND LIVESTOCK PRODUCTS · AGRICULTURAL, FORESTRY AND FISHERY SERVICES · MISCELLANEOUS AGRICULTURAL PRODUCTS · PLASTICS AND SYNTHETIC MATERIALS · CHEMICALS AND SELECTED CHEMICAL PRODUCTS · CHEMICAL AND FERTILIZER MINERAL MINING · PETROLEUM REFINING AND RELATED INDUSTRIES · ELECTRICITY, GAS AND WATER · CRUDE PETROLEUM AND NATURAL GAS · COAL MINING · HOTELS, PERSONAL AND REPAIR SERVICES EXCEPT AUTOMOBILE · STATE AND LOCAL GOVERNMENT ENTERPRISES · FEDERAL GOVERNMENT ENTERPRISES · TRANSPORTATION AND WAREHOUSING · MEDICAL AND EDUCATIONAL SERVICES, NONPROFIT ORGANIZATIONS · RADIO AND TELEVISION BROADCASTING · AUTOMOBILE REPAIR AND SERVICES · AMUSEMENTS · COMMUNICATIONS, EXCEPT RADIO AND TELEVISION BROADCASTING · WHOLESALE AND RETAIL TRADE · FINANCE AND INSURANCE · BUSINESS SERVICES · REAL ESTATE AND RENTAL · MAINTENANCE AND REPAIR CONSTRUCTION · RESEARCH AND DEVELOPMENT · BUSINESS TRAVEL, ENTERTAINMENT AND GIFTS · OFFICE SUPPLIES · SCRAP, USED AND SECONDHAND GOODS

	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59
1	.0002	.0001	.0002	.0001	.0002	.0002	.0004	.0002	.0004	.0004	.0002	.0003	.0002	.0008	.0015	.0003	.0002	.0029	.0002	.0003	.0002	.0002	.0003	.0001
2	.0001	.0001	.0001	.0001	.0001	.0001	.0006	.0001	.0002	.0004	.0016	.0007	.0002	.0002	.0003	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001	.0001
3	.0002	.0001	.0004	.0002	.0001	.0001	.0002	.0027	.0003	.0005	.0079	.0036	.0003	.0035	.0005	.0003	.0001	.0001	.0001	.0001	.0001	.0002	.0002	.0001
4	.0004	.0004	.0005	.0003	.0005	.0003	.0009	.0005	.0005	.0005	.0005	.0005	.0002	.0005	.0005	.0004	.0007	.0004	.0002	.0002	.0001	.0004	.0008	.0005
5	.0016	.0005	.0021	.0004	.0006	.0005	.0008	.0023	.0023	.0022	.0015	.0029	.0005	.0060	.0044	.0037	.0013	.0008	.0004	.0004	.0003	.0014	.0013	.0005
6	.0009	.0006	.0008	.0004	.0012	.0005	.0013	.0008	.0023	.0043	.0007	.0011	.0010	.0089	.0021	.0067	.0016	.0036	.0017	.0023	.0012	.0019	.0039	.0005
7	.0036	.0022	.0041	.0012	.0093	.0019	.0028	.0039	.0049	.0057	.0028	.0036	.0015	.0072	.0063	.0080	.0197	.0365	.0034	.0020	.0014	.0196	.0194	.0018
8	.0087	.0079	.0082	.0067	.0113	.0066	.0185	.0099	.0155	.0237	.0127	.0165	.0467	.0290	.0178	.0205	.0581	.3671	.1788	.0206	.0393	.0221	.0327	.0090
9	.0016	.0015	.0040	.0008	.0023	.0011	.0052	.0020	.0072	.0066	.0061	.0034	.0007	.0057	.0037	.0117	.0046	.0018	.0006	.0012	.0006	.0071	.0140	.0012
10	.0008	.0003	.0008	.0002	.0003	.0002	.0009	.0005	.0007	.0005	.0002	.0002	.0002	.0005	.0006	.0004	.0005	.0003	.0001	.0002	.0001	.0011	.0009	.0002
11	.0017	.0011	.0034	.0009	.0014	.0011	.0031	.0017	.0016	.0022	.0012	.0013	.0007	.0024	.0045	.0014	.0018	.0011	.0007	.0007	.0005	.0028	.0025	.0011
12	.0021	.0012	.0032	.0047	.0014	.0013	.0010	.0010	.0013	.0017	.0032	.0054	.0199	.0011	.0012	.0010	.0011	.0010	.0008	.0007	.0005	.0011	.0013	.0016
13	.0027	.0011	.0046	.0027	.0011	.0011	.0020	.0019	.0017	.0030	.0010	.0009	.0008	.0024	.0019	.0010	.0012	.0008	.0006	.0007	.0005	.0017	.0016	.0010
14	.0006	.0007	.0009	.0005	.0016	.0165	.0002	.0005	.0004	.0006	.0005	.0010	.0002	.0004	.0004	.0003	.0005	.0003	.0002	.0002	.0001	.0006	.0013	.0077
15	.0043	.0017	.0039	.0014	.0051	.0026	.0065	.0034	.0040	.0046	.0036	.0050	.0048	.0138	.0082	.0052	.0037	.0030	.0015	.0016	.0015	.0034	.0044	.0020
16	.0007	.0006	.0007	.0005	.0007	.0005	.0059	.0007	.0008	.0012	.0006	.0007	.0012	.0013	.0015	.0011	.0012	.0008	.0005	.0007	.0004	.0035	.0014	.0005
17	.0009	.0004	.0011	.0004	.0005	.0005	.0005	.0007	.0005	.0007	.0004	.0004	.0006	.0006	.0005	.0004	.0004	.0003	.0003	.0004	.0002	.0005	.0006	.0004
18	.0011	.0003	.0007	.0003	.0004	.0003	.0004	.0008	.0005	.0004	.0004	.0004	.0003	.0004	.0008	.0004	.0005	.0003	.0003	.0003	.0002	.0005	.0005	.0003
19	.0018	.0014	.0030	.0010	.0014	.0011	.0011	.0022	.0013	.0022	.0008	.0008	.0005	.0015	.0024	.0008	.0011	.0012	.0005	.0005	.0003	.0013	.0014	.0010
20	.0009	.0008	.0015	.0007	.0010	.0008	.0023	.0011	.0011	.0017	.0009	.0011	.0026	.0013	.0013	.0011	.0013	.0011	.0008	.0013	.0007	.0013	.0019	.0007
21	.0007	.0012	.0028	.0011	.0006	.0015	.0007	.0007	.0005	.0008	.0007	.0011	.0026	.0016	.0007	.0022	.0007	.0011	.0037	.0100	.0041	.0005	.0007	.0011
22	.0013	.0027	.0018	.0024	.0009	.0026	.0007	.0007	.0007	.0009	.0008	.0010	.0017	.0008	.0007	.0007	.0008	.0007	.0007	.0011	.0006	.0008	.0010	.0024
23	.0064	.0403	.0071	.0381	.0056	.0558	.0008	.0017	.0011	.0019	.0009	.0008	.0007	.0011	.0011	.0010	.0016	.0010	.0006	.0010	.0005	.0019	.0035	.0372
24	.0094	.0009	.0014	.0009	.0009	.0009	.0006	.0007	.0007	.0010	.0011	.0011	.0006	.0008	.0008	.0008	.0007	.0007	.0012	.0016	.0008	.0007	.0008	.0008
25	.0153	.0038	.0130	.0023	.0033	.0030	.0016	.0033	.0028	.0035	.0024	.0018	.0010	.0023	.0027	.0019	.0028	.0022	.0009	.0011	.0008	.0035	.0034	.0023
26	.0086	.0056	.0150	.0045	.0048	.0100	.0033	.0049	.0048	.0075	.0060	.0057	.0027	.0065	.0031	.0032	.0035	.0035	.0051	.0049	.0028	.0033	.0039	.0076
27	.0085	.0073	.0081	.0041	.0025	.0097	.0015	.0031	.0027	.0033	.0028	.0034	.0012	.0021	.0025	.0020	.0024	.0015	.0010	.0016	.0009	.0026	.0034	.0061
28	.0108	.0015	.0022	.0013	.0051	.0011	.0011	.0037	.0020	.0028	.0036	.0026	.0006	.0012	.0025	.0011	.0010	.0019	.0007	.0007	.0004	.0013	.0011	.0008
29	.0102	.0091	.0097	.0036	.0031	.0055	.0021	.0026	.0022	.0030	.0019	.0018	.0016	.0022	.0026	.0020	.0024	.0021	.0009	.0013	.0008	.0034	.0046	.0092
30	.0017	.0008	.0017	.0009	.0010	.0007	.0010	.0009	.0008	.0012	.0007	.0007	.0005	.0010	.0012	.0007	.0007	.0006	.0004	.0005	.0003	.0009	.0010	.0008
31	.0026	.0030	.0070	.0041	.0023	.0026	.0015	.0021	.0020	.0026	.0025	.0024	.0021	.0020	.0019	.0017	.0023	.0013	.0019	.0022	.0014	.0020	.0020	.0023
32	.0074	.0019	.0132	.0014	.0016	.0021	.0010	.0020	.0017	.0024	.0019	.0015	.0006	.0016	.0039	.0009	.0016	.0010	.0007	.0009	.0005	.0015	.0019	.0016
33	.0010	.0011	.0013	.0007	.0013	.0009	.0011	.0015	.0054	.0022	.0011	.0015	.0019	.0028	.0023	.0022	.0519	.0108	.0054	.0023	.0018	.0064	.0113	.0010
34	.0193	.0038	.0146	.0027	.0041	.0033	.0025	.0077	.0045	.0061	.0061	.0058	.0015	.0034	.0059	.0021	.0038	.0039	.0028	.0017	.0013	.0035	.0040	.0035
35	.0240	.0076	.0307	.0056	.0188	.0070	.0080	.0097	.0136	.0215	.0170	.0168	.0042	.0074	.0167	.0058	.0080	.0067	.0038	.0053	.0090	.0083	.0110	.0060
36	1.4975	.0222	.0503	.0114	.0117	.0097	.0089	.0120	.0097	.0152	.0094	.0098	.0045	.0113	.0135	.0081	.0155	.0080	.0045	.0058	.0039	.0172	.0366	.0140
37	.1688	1.2941	.0116	.0724	.0027	.0024	.0013	.0020	.0015	.0024	.0015	.0015	.0007	.0022	.0026	.0018	.0045	.0018	.0008	.0012	.0007	.0051	.0128	.0031
38	.0594	.1027	1.3074	.0583	.0225	.0440	.0097	.0154	.0170	.0220	.0670	.0141	.0099	.0173	.0193	.0127	.0537	.0162	.0099	.0113	.0079	.0244	.0499	.0491
39	.0099	.0240	.0785	1.0922	.0032	.0032	.0009	.0014	.0013	.0018	.0042	.0011	.0007	.0018	.0020	.0014	.0052	.0017	.0008	.0011	.0007	.0040	.0099	.0042
40	.0136	.0130	.0271	.0049	1.1470	.0805	.0038	.0385	.0063	.0115	.0077	.0094	.0022	.0044	.0075	.0034	.0158	.0156	.0028	.0043	.0023	.0054	.0083	.0053
41	.0022	.0018	.0061	.0009	.0770	1.0139	.0017	.0154	.0031	.0063	.0012	.0014	.0012	.0014	.0024	.0016	.0030	.0021	.0018	.0042	.0019	.0024	.0043	.0216
42	.0127	.0102	.0149	.0082	.0153	.0098	1.1720	.0153	.0271	.0316	.0166	.0208	.0331	.0160	.0196	.0160	.0193	.0172	.0116	.0170	.0097	.0165	.0181	.0085
43	.0012	.0008	.0012	.0006	.0021	.0009	.0010	1.0534	.0032	.0017	.0020	.0031	.0011	.0034	.0084	.0048	.0022	.0054	.0027	.0010	.0009	.0024	.0034	.0007
44	.0044	.0023	.0050	.0016	.0157	.0053	.0164	.0892	1.0529	.0437	.0084	.0115	.0119	.0179	.0146	.0180	.0193	.0119	.0053	.0027	.0063	.0141	.0124	.0033
45	.0163	.0085	.0148	.0056	.0493	.0219	.2697	.0602	.5859	1.3012	.0203	.0302	.0268	.0506	.0344	.0305	.0414	.0230	.0095	.0092	.0099	.0812	.0335	.0156
46	.0003	.0002	.0005	.0002	.0020	.0003	.0005	.0064	.0014	.0015	1.0402	.0045	.0011	.0007	.0005	.0012	.0006	.0038	.0021	.0051	.0022	.0007	.0007	.0002
47	.0064	.0054	.0072	.0143	.0107	.0400	.0287	.0349	.0620	.1323	.5644	1.4403	.0052	.0084	.0084	.0060	.0085	.0063	.0039	.0058	.0035	.0122	.0104	.0038
48	.0008	.0007	.0009	.0016	.0012	.0005	.0031	.0037	.0064	.0136	.0570	.1451	1.0149	.0013	.0012	.0009	.0016	.0038	.0012	.0008	.0006	.0020	.0029	.0005
49	.0022	.0011	.0015	.0007	.0024	.0023	.0036	.0015	.0037	.0060	.0023	.0040	.0134	1.1187	.0795	.0427	.0017	.0025	.0021	.0032	.0101	.0031	.0023	.0011
50	.0083	.0089	.0097	.0045	.0187	.0253	.0091	.0100	.0230	.0266	.0104	.0164	.0126	.0306	1.0410	.0158	.0133	.0180	.0069	.0111	.0068	.0273	.0149	.0104
51	.0074	.0057	.0077	.0020	.0069	.0035	.0064	.0050	.0116	.0221	.0038	.0050	.0060	.3882	.0617	1.5524	.0043	.0052	.0028	.0040	.0047	.0067	.0059	.0028
52	.0028	.0019	.0030	.0011	.0029	.0013	.0017	.0016	.0021	.0029	.0053	.0089	.0030	.0042	.0030	.0033	1.0058	.0020	.0021	.0024	.0014	.0098	.0064	.0013
53	.0001	.0001	.0002	.0001	.0003	.0001	.0002	.0001	.0002	.0002	.0001	.0002	.0001	.0006	.0014	.0005	.0002	1.1692	.0001	.0001	.0001	.0001	.0002	.0001
54	.0040	.0044	.0039	.0051	.0051	.0039	.0080	.0046	.0072	.0109	.0123	.0248	.1152	.0532	.0368	.0451	.0189	.1946	1.2804	.1103	.2201	.0087	.0118	.0039
55	.0049	.0055	.0049	.0067	.0062	.0042	.0097	.0062	.0093	.0153	.0310	.0723	.1956	.0669	.0217	.1969	.0138	.0859	.3640	1.0817	.4334	.0087	.0114	.0041
56	.0004	.0004	.0004	.0005	.0005	.0004	.0007	.0005	.0008	.0013	.0030	.0070	.0252	.0037	.0017	.0085	.0011	.0071	.0382	.0434	1.0218	.0006	.0008	.0003
57	.0237	.0047	.0054	.0025	.0195	.0068	.0071	.0058	.0165	.0238	.0083	.0169	.0066	.2500	.1785	.1524	.1381	.0075	.0030	.0050	.0046	1.0456	.0322	.0041
58	.0460	.0746	.0289	.0324	.0503	.0272	.0411	.0630	.0439	.0784	.0184	.0347	.0220	.1332	.1485	.1165	.3606	.1266	.0314	.0758	.0335	.4673	1.2814	.0574
59	.0021	.0042	.0016	.0012	.0055	.0017	.0018	.0026	.0025	.0049	.0008	.0014	.0011	.0046	.0062	.0042	.0118	.0056	.0016	.0039	.0017	.0153	.0412	1.0754
60	.0197	.0232	.0244	.0251	.0293	.0414	.0142	.0166	.0274	.0342	.0250	.0316	.0329	.0258	.0223	.0293	.0432	.0262	.0264	.0559	.0266	.0523	.0880	.0242
61	.0596	.0580	.0523	.0393	.0527	.0439	.0208	.0597	.0304	.0451	.0256	.0232	.0110	.0319	.0299	.0367	.0300	.0278	.0172	.0202	.0118	.0376	.0536	.0750
62	.0078	.0085	.0454	.0117	.0157	.0067	.0044	.0061	.0084	.0158	.0041	.0028	.0017	.0067	.0066	.0070	.0074	.0071	.0021	.0022	.0014	.0133	.0128	.0065
63	.0145	.0165	.0167	.0165	.0194	.0255	.00 2	.0129	.0170	.0217	.0154	.0189	.0189	.0165	.0144	.0186	.0264	.0164	.0157	.0323	.0155	.0321	.0544	.0207
64	.0050	.0051	.0050	.0043	.0049	.0040	.0126	.0067	.0052	.0059	.0048	.0046	.0062	.0070	.0057	.0061	.0076	.0101	.0035	.0043	.0031	.0095	.0073	.0046
65	.0602	.0453	.0971	.0551	.0970	.0347	.0571	.0560	.0847	.0875	.0930	.0980	.0283	.0718	.0588	.0710	.0791	.0730	.0512	.0334	.0296	.0750	.0777	.0598
66	.0102	.0098	.0105	.0076	.0111	.0082	.0053	.0100	.0074	.0102	.0071	.0070	.0031	.0070	.0062	.0075	.0069	.0066	.0043	.0046	.0030	.0078	.0100	.0118
67	.0047	.0044	.0045	.0042	.0052	.0038	.0080	.0055	.0055	.0052	.0077	.0065	.0024	.0056	.0053	.0059	.0057	.0048	.0020	.0023	.0015	.0043	.0061	.0044
68	.0041	.0027	.0046	.0028	.0079	.0028	.0048	.0042	.0057	.0063	.0173	.0165	.0033	.0051	.0039	.0052	.0062	.0067	.0073	.0053	.0034	.0046	.0056	.0028
69	.0019	.0016	.0018	.0014	.0021	.0016	.0044	.0020	.0019	.0025	.0019	.0026	.0071	.0023	.0028	.0026	.0026	.0024	.0020	.0034	.0018	.0024	.0025	.0014
70	.0012	.0011	.0012	.0011	.0013	.0010	.0024	.0012	.0013	.0014	.0014	.0016	.0025	.0014	.0015	.0014	.0017	.0013	.0011	.0015	.0009	.0013	.0017	.0010
71	.0027	.0024	.0026	.0020	.0023	.0019	.0025	.0023	.0027	.0026	.0028	.0028	.0024	.0031	.0026	.0032	.0028	.0037	.0081	.0020	.0026	.0028	.0027	.0019
72	.0767	.0542	.0727	.0438	.0594	.0617	.0581	.0629	.0849	.0854	.0994	.0903	.0467	.0925	.0681	.0830	.0808	.0757	.0812	.0691	.0420	.0569	.0634	.0472
73	.0258	.0377	.0245	.0238	.0260	.0247	.0264	.0231	.0238	.0242	.0260	.0293	.0470	.0284	.0213	.0277	.0267	.0253	.0274	.0296	.0202	.0250	.0279	.0187
74	.0095	.0069	.0096	.0060	.0087	.0059	.0208	.0077	.0089	.0100	.0089	.0098	.0101	.0100	.0091	.0088	.0112	.0100	.0081	.0085	.0090	.0095	.0110	.0061
75	.0296	.0249	.0284	.0218	.0334	.0248	.0702	.0319	.0301	.0395	.0309	.0408	.1133	.0367	.0450	.0408	.0422	.0386	.0323	.0538	.0290	.0383	.0392	.0219
76	.0307	.0671	.0324	.1264	.0300	.0445	.0610	.0250	.0321	.0295	.0375	.0410	.0710	.0374	.0323	.0434	.0385	.0328	.0598	.1056	.0587	.0312	.0399	.0289
77	.0125	.0158	.0215	.0197	.0135	.0120	.0174	.0114	.0175	.0185	.0139	.0165	.0154	.0148	.0124	.0173	.0136	.0148	.0291	.0334	.0195	.0179	.0142	.0124
78	.0011	.0003	.0013	.0002	.0002	.0002	.0002	.0012	.0003	.0006	.0002	.0002	.0001	.0011	.0009	.0010	.0013	.0004	.0001	.0002	.0001	.0041	.0029	.0002
79	.0018	.0014	.0018	.0012	.0019	.0013	.0052	.0020	.0021	.0021	.0019	.0020	.0024	.0021	.0022	.0021	.0026	.0018	.0012	.0014	.0009	.0017	.0025	.0015
80	.0153	.0133	.0131	.0117	.0174	.0115	.0334	.0169	.0169	.0167	.0193	.0176	.0074	.0154	.0176	.0142	.0251	.0139	.0068	.0072	.0051	.0158	.0282	.0170
81	.0027	.0045	.0402	.0030	.0040	.0052	.0055	.0135	.0116	.0247	.0032	.0022	.0014	.0177	.0034	.0021	.0031	.0015	.0010	.0012	.0009	.0032	.0035	.0041
	.0046	.0022	.0030	.0018	.0051	.0024	.0032	.0025	.0035	.0043	.0032	.0042	.0052	.0286	.0406	.0184	.0098	.0180	.0102	.0135	.0070	.0053	.0080	.0023

	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81
1	.0001	.0001	.0001	.0001	.0004	.0001	.0001	.0010	.0003	.0008	.0028	.0003	.0004	.0002	.0001	.0004	.0001	.0001	.0004	.0014	.0047	.0021
2	.0001	.0001	.0001	.0001	.0001	.0002	.0003	.0005	.0002	.0001	.0001	.0001	.0002	.0001	.0001	.0002	.0002	.0012	.0010	.0006	.0002	.0006
3	.0001	.0001	.0002	.0001	.0001	.0002	.0001	.0013	.0003	.0007	.0001	.0001	.0002	.0001	.0004	.0002	.0001	.0003	.0029	.0004	.0005	.0027
4	.0003	.0002	.0003	.0003	.0004	.0003	.0002	.0005	.0004	.0008	.0007	.0007	.0006	.0006	.0002	.0006	.0002	.0003	.0007	.0008	.0276	.0032
5	.0007	.0003	.0005	.0004	.0004	.0005	.0007	.0106	.0011	.0004	.0003	.0025	.0010	.0003	.0001	.0008	.0007	.0006	.0024	.0015	.0036	.0123
6	.0006	.0003	.0004	.0003	.0015	.0010	.0004	.0125	.0046	.0024	.0017	.0024	.0009	.0020	.0007	.0018	.0004	.0005	.0017	.0022	.0034	.0050
7	.0048	.0008	.0012	.0008	.0013	.0014	.0017	.0174	.0029	.0009	.0011	.0290	.0022	.0015	.0005	.0026	.0012	.0023	.0098	.0042	.0108	.0035
8	.0080	.0063	.0057	.0057	.0892	.0093	.0054	.0120	.0079	.0123	.0114	.0216	.0172	.0111	.0038	.0133	.0074	.0082	.0143	.0197	.3915	.0135
9	.0018	.0005	.0010	.0018	.0006	.0005	.0006	.0011	.0013	.0004	.0003	.0005	.0007	.0004	.0002	.0017	.0005	.0012	.0032	.0052	.0008	.0333
10	.0003	.0001	.0002	.0002	.0003	.0005	.0001	.0007	.0005	.0008	.0001	.0010	.0003	.0001	.0004	.0005	.0002	.0003	.2285	.0008	.0014	.0063
11	.0015	.0006	.0009	.0011	.0018	.0072	.0006	.0011	.0017	.0008	.0004	.0016	.0014	.0005	.0005	.0015	.0006	.0011	.4203	.0028	.0039	.0381
12	.0011	.0009	.0063	.0006	.0024	.0109	.0008	.0015	.0023	.0005	.0007	.0014	.0006	.0010	.0008	.0015	.0005	.0013	.0038	.0015	.0051	.0077
13	.0017	.0009	.0009	.0016	.0008	.0016	.0010	.0030	.0032	.0255	.0008	.0016	.0016	.0008	.0138	.0032	.0007	.0023	.0992	.0027	.0077	.0903
14	.0003	.0003	.0055	.0003	.0003	.0007	.0004	.0002	.0003	.0001	.0001	.0001	.0002	.0001	.0001	.0002	.0002	.0009	.0013	.0003	.0004	.0045
15	.0025	.0020	.0033	.0017	.0025	.0033	.0031	.0258	.0031	.0124	.0234	.0041	.0034	.0039	.0025	.0159	.0017	.0047	.0070	.1637	.0137	.0308
16	.0008	.0004	.0004	.0006	.0006	.0005	.0005	.0102	.0007	.0021	.0069	.0043	.0012	.0009	.0004	.0104	.0005	.0004	.0089	.0122	.0042	.0023
17	.0005	.0004	.0004	.0006	.0003	.0005	.0007	.0043	.0009	.0004	.0004	.0004	.0008	.0004	.0002	.0041	.0006	.0023	.0052	.0007	.0012	.0121
18	.0003	.0005	.0003	.0003	.0003	.0005	.0012	.0107	.0005	.0004	.0004	.0005	.0006	.0003	.0002	.0006	.0007	.00 3	.0305	.0008	.0058	.0022
19	.0010	.0005	.0008	.0010	.0006	.0016	.0008	.0078	.0045	.0006	.0005	.0130	.0010	.0004	.0003	.0009	.0006	.0024	.0393	.0018	.0036	.0450
20	.0015	.0012	.0006	.0013	.0009	.0009	.0008	.0015	.0014	.0015	.0015	.0014	.0020	.0017	.0006	.0230	.0009	.0007	.0049	.0077	.0013	.0156
21	.0007	.0004	.0013	.0007	.0019	.0004	.0004	.0005	.0009	.0005	.0005	.0004	.0007	.0005	.0002	.0064	.0006	.0005	.0037	.0008	.0012	.0111
22	.0020	.0008	.0022	.0026	.0011	.0037	.0006	.0006	.0018	.0005	.0005	.0005	.0007	.0005	.0002	.0056	.0005	.0010	.0135	.0008	.0020	.0075
23	.0036	.0025	.0475	.0051	.0011	.0008	.0019	.0006	.0013	.0003	.0003	.0004	.0007	.0003	.0002	.0015	.0006	.0030	.0030	.0012	.0008	.0143
24	.0007	.0005	.0008	.0006	.0014	.0034	.0008	.0010	.0199	.0003	.0003	.0009	.0010	.0004	.0007	.0009	.0004	.0 12	.0092	.0008	.0020	.0119
25	.0020	.0013	.0071	.0014	.0010	.0020	.0012	.0014	.0056	.0007	.0005	.0008	.0009	.0005	.0004	.0022	.0011	.0023	.0390	.0027	.0019	.0246
26	.0048	.0030	.0077	.0052	.0088	.0116	.0058	.0048	.2130	.0013	.0011	.0022	.0064	.0020	.0010	.0038	.0020	.0036	.0629	.0049	.0075	.1875
27	.0068	.0017	.0070	.0105	.0010	.0020	.0015	.0012	.0036	.0005	.0005	.0007	.0010	.0004	.0004	.0017	.0009	.0036	.0132	.0023	.0017	.0289
28	.0007	.0012	.0026	.0006	.0008	.0013	.0026	.0018	.0021	.0008	.0006	.0008	.0007	.0004	.0007	.0009	.0011	.0088	.0223	.0022	.0014	.0059
29	.0041	.0023	.0055	.0054	.0012	.0030	.0026	.0039	.0043	.0013	.0009	.0015	.0012	.0006	.0010	.0025	.0013	.0080	.0534	.0038	.0029	.0234
30	.0015	.0006	.0006	.0020	.0006	.0016	.0005	.0223	.0017	.0053	.0005	.0012	.0008	.0005	.0034	.0021	.0007	.0011	.0537	.0018	.0054	.0215
31	.0025	.0047	.0029	.0026	.0017	.0038	.0144	.0017	.0031	.0014	.0024	.0026	.0024	.0014	.0021	.0014	.0059	.0542	.0070	.0020	.0028	.0355
32	.0011	.0006	.0017	.0011	.0010	.0015	.0009	.0010	.0177	.0004	.0003	.0006	.0008	.0003	.0003	.0010	.0005	.0015	.0280	.0019	.0013	.0434
33	.0066	.0007	.0007	.0006	.0027	.0010	.0012	.0011	.0012	.0005	.0005	.0014	.0008	.0005	.0003	.0007	.0007	.0034	.0015	.0016	.0103	.0116
34	.0027	.0016	.0099	.0026	.0017	.0024	.0022	.0034	.0106	.0014	.0010	.0023	.0016	.0007	.0009	.0024	.0011	.0053	.0248	.0061	.0041	.0677
35	.0185	.0135	.0112	.0080	.0043	.0054	.0094	.0072	.0283	.0020	.0019	.0026	.0030	.0016	.0016	.0043	.0021	.0102	.0252	.0175	.0068	.0528
36	.0090	.0074	.0191	.0075	.0046	.0089	.0124	.0109	.0198	.0045	.0047	.0050	.0038	.0025	.0068	.0083	.0055	.03 0	.0760	.0233	.0096	.1658
37	.0015	.0012	.0025	.0010	.0007	.0012	.0016	.0015	.0026	.0006	.0006	.0007	.0005	.0004	.0008	.0011	.0008	.0049	.0092	.0032	.0013	.0202
38	.0192	.0155	.0372	.0124	.0087	.0130	.0186	.0118	.0457	.0045	.0050	.0065	.0061	.0035	.0037	.0100	.0078	.0516	.0752	.0243	.0174	.2935
39	.0017	.0010	.0025	.0009	.0011	.0009	.0013	.0009	.0030	.0003	.0004	.0005	.0004	.0003	.0003	.0007	.0006	.0035	.0051	.0019	.0012	.0184
40	.0054	.0059	.0060	.0023	.0057	.0038	.0117	.0077	.0112	.0017	.0024	.0028	.0032	.0015	.0019	.0026	.0051	.0418	.0100	.0066	.0047	.0137
41	.0046	.0013	.0015	.0005	.0015	.0011	.0031	.0010	.0015	.0005	.0006	.0008	.0006	.0005	.0005	.0008	.0015	.0113	.0014	.0028	.0013	.0026
42	.0182	.0111	.0074	.0150	.0261	.0138	.0159	.0168	.0174	.0278	.0248	.0322	.0227	.0437	.0233	.813	.0115	.0082	.0161	.6885	.0191	.0708
43	.0010	.0008	.0007	.0006	.0017	.0015	.0019	.0026	.0167	.0009	.0008	.0018	.020	.0006	.0006	.0010	.0010	.0064	.0056	.0028	.0059	.0053
44	.0045	.0014	.0027	.0016	.0050	.0021	.0020	.0067	.0052	.0036	.0025	.0041	.0058	.0030	.0010	.0063	.0014	.0045	.0077	.0277	.0103	.0363
45	.0148	.0077	.0096	.0068	.0216	.0088	.0111	.0286	.0131	.0180	.0114	.0182	.0173	.0213	.0081	.0760	.0061	.0152	.0184	.4816	.0212	.0466
46	.0002	.0002	.0002	.0001	.0012	.0007	.0002	.0003	.0004	.0001	.0001	.0002	.0012	.0001	.0001	.0003	.0003	.0005	.0007	.0008	.0016	.0007
47	.0040	.0049	.0144	.0029	.0045	.0046	.0115	.0059	.0044	.0035	.0036	.0043	.0045	.0 34	.0025	.0093	.0054	.0391	.0069	.0546	.0064	.0113
48	.0005	.0006	.0016	.0004	.0009	.0006	.0012	.0008	.0005	.0005	.0005	.0006	.0006	.0005	.0003	.0011	.0006	.0040	.0009	.0058	.0049	.0014
49	.0010	.0006	.0014	.0010	.0014	.0020	.0012	.0055	.0077	.0023	.0018	.0022	.0011	.0020	.0008	.0025	.0007	.0012	.0039	.0061	.0027	.0075
50	.0060	.0035	.0138	.0055	.0064	.0122	.0050	.0117	.0471	.0033	.0033	.0059	.0052	.0049	.0021	.0080	.0029	.0086	.0248	.0259	.0114	.0243
51	.0026	.0013	.0035	.0026	.0025	.0027	.0017	.0333	.0100	.0035	.0031	.0043	.0024	.0028	.0013	.0043	.0017	.0024	.0069	.0156	.0089	.1294
52	.0025	.0044	.0016	.0019	.0020	.0048	.0142	.0017	.0108	.0015	.0025	.0026	.0017	.0014	.0020	.0014	.0059	.0537	.0029	.0033	.0033	.0041
53	.0001	.0001	.0001	.0001	.0002	.0002	.0001	.0005	.0002	.0003	.0009	.0001	.0002	.0001	.0001	.0002	.0001	.0001	.0003	.0016	.0014	.0011
54	.0051	.0031	.0033	.0053	.0435	.0046	.0027	.0065	.0055	.0064	.0088	.0090	.0074	.0062	.0019	.0065	.0232	.0038	.0062	.0092	.1242	.0091
55	.0064	.0067	.0042	.0068	.1801	.0058	.0036	.0096	.0062	.0063	.0071	.0082	.0086	.0090	.0026	.0109	.0323	.0049	.0061	.0119	.0853	.0220
56	.0004	.0004	.0004	.0004	.0078	.0004	.0004	.0006	.0005	.0006	.0012	.0006	.0021	.0005	.0002	.0007	.0018	.0005	.0005	.0009	.0059	.0012
57	.0043	.0021	.0044	.0021	.0027	.0039	.0040	.0082	.0124	.0024	.0024	.0029	.0021	.0021	.0014	.0041	.0022	.0111	.0121	.0178	.0056	.0238
58	.0520	.0092	.0314	.0112	.0183	.0107	.0184	.0247	.0184	.0052	.0057	.0114	.0070	.0057	.0034	.0160	.0092	.0335	.0395	.0608	.0207	.0346
59	.0018	.0004	.0011	.0004	.0009	.0004	.0007	.0009	.0008	.0002	.0002	.0004	.0003	.0003	.0001	.0007	.0004	.0013	.0014	.0029	.0009	.0015
60	1.0918	.0248	.0214	.0112	.0246	.0583	.0225	.0207	.0129	.0061	.0061	.0097	.0134	.0100	.0047	.0126	.0136	.0338	.0165	.0200	.0366	.0311
61	.0340	1.2223	.0427	.0153	.0319	.0154	.1031	.0334	.0370	.0123	.0169	.0285	.0304	.0130	.0102	.0231	.0105	.0150	.0217	.0276	.0211	.0321
62	.0035	.0441	1.2102	.0014	.0162	.0030	.0249	.0026	.0055	.0011	.0012	.0018	.0021	.0017	.0008	.0042	.0014	.0034	.0046	.0074	.0031	.0129
63	.6022	.0865	.0144	1.0331	.0156	.0332	.0229	.0136	.0095	.0043	.0045	.0072	.0093	.0065	.0032	.0085	.0102	.0196	.0106	.0129	.0216	.0192
64	.0060	.0257	.0041	.0032	1.0050	.0046	.0050	.0047	.0056	.0043	.0044	.0041	.0140	.0189	.0057	.0326	.0069	.0030	.0047	.0099	.0053	.0058
65	.0781	.0435	.0266	.0225	.2128	1.0839	.0358	.0304	.0362	.0223	.0237	.0261	.0239	.0313	.0102	.0366	.0183	.0431	.0420	.0641	.4677	.1263
66	.0078	.1556	.0070	.0042	.0097	.0268	1.0145	.0074	.0095	.0030	.0038	.0056	.0089	.0067	.0022	.0050	.0091	.0038	.0046	.0066	.0146	.0081
67	.0029	.0020	.0025	.0028	.0029	.0021	.0034	1.0340	.0033	.0051	.0045	.0096	.0064	.0043	.0015	.0098	.0056	.0025	.0060	.0071	.1531	.0056
68	.0055	.0041	.0024	.0033	.0162	.0285	.0036	.0124	1.0202	.0029	.0019	.0042	.0108	.0061	.0025	.0080	.0037	.0046	.0030	.0052	.0174	.0058
69	.0036	.0017	.0011	.0030	.0022	.0019	.0017	.0029	.0028	1.0066	.0039	.0026	.0039	.0038	.0015	.0657	.0022	.0013	.0022	.0037	.0028	.0024
70	.0017	.0008	.0008	.0015	.0014	.0020	.0008	.0016	.0014	.2569	1.3115	.0065	.0031	.0022	.0011	.0194	.0029	.0008	.0032	.0021	.0259	.0015
71	.0024	.0016	.0019	.0016	.0012	.0018	.0009	.0020	.0023	.0019	.0021	1.0142	.0017	.0073	.0013	.0014	.0014	.0015	.1043	.0025	.0083	.0026
72	.0354	.0342	.0584	.0243	.0478	.0512	.0442	.0669	.1166	.0299	.0322	.0368	1.0312	.0265	.0144	.0456	.0360	.1060	.0593	.0711	.1165	.0735
73	.0291	.0176	.0228	.0252	.0177	.0368	.0203	.0314	.0459	.0255	.0459	.0238	.0288	1.2653	.0105	.0292	.0481	.0141	.0186	.0255	.0313	.0236
74	.0065	.0064	.0041	.0039	.0086	.0124	.0088	.0102	.0132	.0454	.0116	.0124	.0148	.0237	1.0109	.0364	.0069	.0054	.0104	.0165	.0112	.0107
75	.0571	.0274	.0179	.0474	.0359	.0296	.0269	.0457	.0443	.0616	.0616	.0420	.0617	.0605	.0232	1.0530	.0312	.0202	.0358	.0586	.0453	.0383
76	.1111	.0284	.0399	.1614	.0439	.0510	.0298	.0660	.0615	.0766	.0810	.0835	.0672	.1115	.0226	.0668	1.0355	.0202	.0327	.0491	.0527	.0342
77	.0198	.0777	.0103	.0193	.0241	.0548	.2612	.0154	.0279	.0227	.0410	.0433	.0204	.0216	.0359	.0152	.1039	1.0073	.0136	.0171	.0344	.0171
78	.0006	.0001	.0002	.0001	.0004	.0001	.0001	.0002	.0003	.0001	.0001	.0019	.0001	.0001	.0001	.0001	.0001	.0002	1.0010	.0004	.0002	.0008
79	.0018	.0028	.0011	.0013	.0063	.0025	.0070	.0029	.0020	.0028	.0029	.0050	.0035	.0078	.0045	.0125	.0014	.0011	.0025	1.0040	.0025	.0024
80	.0113	.0081	.0098	.0106	.0143	.0092	.0080	.0193	.0123	.0280	.0240	.0244	.0207	.0213	.0072	.0221	.0044	.0095	.0245	.0275	1.0132	.0193
81	.0082	.0019	.0041	.0125	.0012	.0015	.0015	.0054	.0118	.0007	.0006	.0009	.0020	.0007	.0004	.0021	.0007	.0035	.0036	.0101	.0023	1.0110
	.0025	.0025	.0017	.0012	.0531	.0187	.0016	.0027	.0035	.0065	.0262	.0022	.0024	.0074	.0067	.0039	.0017	.0021	.0033	.0065	.0194	.0062

in any cell of this table gives, per dollar of delivery to final demand made by sector listed at top, the total input directly and indirectly required from industry listed at left. Cells are colored where delivery of sector at left exceeds 1/81 of its total output.

	1 Footwear and other leather products	2 Miscellaneous furniture and fixtures	3 Household furniture	4 Tobacco manufactures	5 Apparel	6 Miscellaneous fabricated textile products	7 Drugs, cleaning and toilet preparations	8 Food and kindred products	9 Special-industry machinery and equipment	10 Ordnance and accessories	11 Aircraft and parts	12 Miscellaneous transportation equipment	13 Radio, television and communication equipment	14 Materials-handling machinery and equipment	15 Miscellaneous manufacturing	16 Optical, ophthalmic and photographic equipment	17 Service-industry machines	18 Household appliances	19 Scientific and controlling instruments	20 Office, computing and accounting machines	21 Farm machinery and equipment	22 Engines and turbines	23 Construction, mining and oil-field machinery	24 Miscellaneous electrical machinery, equipment and supplies	25 Metalworking machinery and equipment	26 Motor vehicles and equipment	27 General industrial machinery and equipment	28 Electric lighting and wiring equipment	29 Electric industrial equipment and apparatus	30 Electronic components and accessories	31 Heating, plumbing and structural metal products	32 Machine-shop products	33 Metal containers	34 Stampings, screw-machine products and bolts	35 Other fabricated metal products
	FINAL NONMETAL								FINAL METAL																						BASIC METAL				
FINAL NONMETAL																																			
Footwear and other leather products 1	345		1		15	8									44	1		6	4													3		1	1
Miscellaneous furniture and fixtures 2		40	33			8					29	21		1	7		2	1	17	1	2					6	1				17			1	9
Household furniture 3	1	57	65			9						34	189		2		3	1	3				1			2	2			19	11			1	11
Tobacco manufactures 4				1516				1							1																				
Apparel 5	23	2	2		3271	27	3	52	3	4	15	5	6	1	12	2	2	3	13	3	2	2	3	2	5	14	5	3	6	5	10	3		5	9
Miscellaneous fabricated textile products 6	2	2	6		239	190	4	133				2			9				2							203					3			1	
Drugs, cleaning and toilet preparations 7	1			10	2	2	553	282	2	4	7	3	3	1	20		2	1	9	1	2	1	2		2	25	2	1	1		3	1	7	3	3
Food and kindred products 8	1		37	47			260	14028	1						10				16																
FINAL METAL																																			
Special-industry machinery and equipment 9		1	13				12		168	7	7	1	3	6	3	3	8		8	16	10	3	8		41	8	34		8	1	39	13		3	22
Ordnance and accessories 10									3	111	379		196		1	3			138	3	9		1		1	8	1		9	29	1			3	2
Aircraft and parts 11		2				1			12	1288	3230	23	69	3	6		19	1	76	20	7	30	3	2	27	12	84		8		16	7	9	8	7
Miscellaneous transportation equipment 12		1							11	22	4	337	1	6	15	1	1	9	7		7	27	20		1	27	25		35		76	7		1	7
Radio, television and communication equipment 13		3	1						31	215	460	8	466		18	9	9	1	50	28			3	9		159	9	7	69	120	1	1		1	3
Materials-handling machinery and equipment 14			3						16		7	21		55			3				1	4	23		12	7	38		3		11	1		1	9
Miscellaneous manufacturing 15	16	31	21	9	345	51	7	40	3	16	30	12	14	40	389	4	5	6	26	4	3	4	2	1	12	26	1	16	3	6	10	1	2	25	27
Optical, ophthalmic and photographic equipment 16	4								7	4	35	1	19			113		7	26					1	1	1	1		5	1	2			3	1
Service-industry machines 17		19					2		16	25	11	12	5	3	2		140	140	8		1		3		9	39	43	3	2		89	1		9	11
Household appliances 18		1	5				1		4	1	38	25	3		15		169	52	4		12		1	5	9			1	4	3	73		7	12	17
Scientific and controlling instruments 19	7	12			3	9	34		6	141	263	7	45	1	9	29	38	146	270	10	4	3	3	8	4	133	31	8	90	17	96	3	1	9	28
Office, computing and accounting machines 20		4							5	5	8		9	2	19	1			62	258			1	1					4	17	3	1		3	1
Farm machinery and equipment 21		1							9	7	3	26		7	2		1		2		125	40	73	1	8	32	11	1	1		19	1		5	9
Engines and turbines 22									2	7	26	152		21			5				163	272	108	2	9	115	65		108		43	11		7	9
Construction, mining and oil-field machinery 23		1							26	3	3	27	1	73		1	2	2	3		43	82	233	3	9	13	37	1	8	3	32	7		1	25
Miscellaneous electrical machinery, equipment and supplies 24								5	1	2	61	6	3	3	1	7		1	4	1	26	52	6	76		468	5	89	15	3	1	4		1	3
Metalworking machinery and equipment 25		5	4			1	1	18	78	70	330	26	37	24	6	9	9	38	57	27	60	50	71	29	277	342	89	17	79	20	59	38	34	56	227
Motor vehicles and equipment 26		5							9	27	109	67	1	14	8		37	10	68		55	76	61	70	231	9030	31		11		43	9		130	42
General industrial machinery and equipment 27	1	3	1			2		2	186	40	184	77	11	99	7		46	52	27	19	190	95	238	34	159	173	344	5	60	4	124	20	19	3	71
Electric lighting and wiring equipment 28	3	2	4	1				30	2	74	22	17	92	4	21	8	19	38	16	12	2	1	5	76	3	127	5	123	115	28	22	2	1	20	20
Electric industrial equipment and apparatus 29		1	1					11	130	137	57	167	134	71	41	27	264	201	161	69	21	51	47	48	133	66	258	105	455	118	122	10	3	21	33
Electronic components and accessories 30	3		1						9	5	102	1	1456	1	14				138	123			1	28		24	2	11	187	216	11			5	7
BASIC METAL																																			
Heating, plumbing and structural metal products 31	1	26	14						37	12	10	229	5	18	3		69	76	6		8	4	66		18	31	92	7	19	2	201	4	13	39	76
Machine-shop products 32			1					1	14	498	169	18	8	23	16	1	3	5	35	7	50	89	19	17	30	195	29	5	12	4	44	142	13	18	26
Metal containers 33				10			144	2023											11						1						4		4	17	6
Stampings, screw-machine products and bolts 34	2	15	23	1		1	29	232	42	41	328	25	150	26	96	12	105	259	84	33	109	66	43	50	130	942	56	84	102	83	208	11	37	133	171
Other fabricated metal products 35	32	73	265	12	23	6	77	113	56	64	175	105	96	31	123	21	79	160	77	18	23	8	54	9	100	1093	96	54	57	48	339	44	11	130	330
Primary nonferrous metal manufacturing 36	2	27	37	9			1	47	151	302	481	92	157	17	330	56	151	206	187	56	26	97	30	216	143	347	142	159	492	159	785	163	27	320	582
Nonferrous metal ores mining 37							1												2					2				5							2
Primary iron and steel manufacturing 38		187	105		1	1	1	2	301	83	542	593	75	158	194	12	204	370	90	66	496	302	641	59	371	2664	534	207	394	72	2570	168	1219	983	1680
Iron and ferroalloy ores mining 39																								3	1				4						
BASIC NONMETAL																																			
Stone and clay products 40	10	4	11				16	4	15	17	64	41	25	6	17	39	18	38	17	8	19	19	24	19	36	85	46	21	53	25	67	37	6	38	61
Stone and clay mining and quarrying 41							5	5							1						1		1				12				2				1
Printing and publishing 42	23	2	2	17	18	4	36	163	3	13	14	3	12	1	38	1	1	3	3	10	2	4	2			16	3	1	8	2	6		8	7	22
Glass and glass products 43		75	62				177	804		6	2	26	37		37	23	8	9	15	1		2		1	1	312		89	6	113	40			5	[illegible]
Paperboard containers and boxes 44	51	37	81	94	118	29	269	1170	1	21	13	2	42	1	272	14	25	47	37	5	7	14	4	14	1	33	8	54	27	20	42		37	45	[illegible]
Paper and allied products, except containers 45	38	7	16	93	19	39	77	493	7	9	7	8	36	1	157	67	12	7	23	20	2	3	4	3		111	14	9	54	42	20		12	22	[illegible]
Wooden containers 46	1		1	12				131	1	6					3		15	28	1	1	1										11		1	2	
Lumber and wood products, except containers 47	36	120	544	2			9	5	19	2	29	122	15	1	132		10	8	4	2	12	1	5		7	17	7	4	9	1	25		1	25	[illegible]
Forestry and fishery products 48					187	1		366							4																				
Miscellaneous textile goods and floor coverings 49	55	35	58		106	223		1		1	8	4			46	1			3			1				119			2					1	[illegible]
Rubber and miscellaneous plastics products 50	245	18	177	13	31	90	84	192	42	151	106	45	79	28	252	15	35	158	56	32	112	15	63	95	19	870	21	47	50	24	15	4	41	32	[illegible]
Broad and narrow fabrics, yarn and thread mills 51	107	4	249	2	5208	1351	1	10	4		3	3	2	2	131	1		12	37					1		67	3		2		3				
Paints and allied products 52		33	89			1	18	8	1	3	14	40	4	4	52		15	28	3	3	13	4	6			118	3	15	20	2	29		46	24	[illegible]
Leather tanning and industrial leather products 53	864	3	5		50				4			2	1		45			1	4		4		1			9	1	1	1		1	1	1	1	
Livestock and livestock products 54							7	19751																											
Miscellaneous agricultural products 55				1457	11		3	6366							10				6																
Agricultural, forestry and fishery services 56																					4														
Plastics and synthetic materials 57	3	2	2	141	195		21	19	2		12	37	56	1	161	1	3	13	11	4	1	2	2	11	2	35	1	57	47	27	4		3	20	
Chemicals and selected chemical products 58	1			7	56		1112	292	7	14	21	11	8		59	125	19	25	14	1	3		4	44	5	54	9	17	26	41	27			16	[illegible]
Chemical and fertilizer mineral mining 59								11																											
ENERGY																																			
Petroleum refining and related industries 60	1	4	9	4	8	3	85	377	19	14	41	22	10	5	22	5	9	6	6	5	13	12	18	3	25	63	19	6	21	6	57	21	8	31	[illegible]
Electricity, gas and water 61	14	11	25	8	60	11	36	472	19	24	92	32	22	6	35	8	15	29	18	10	19	13	25	13	30	144	30	16	47	26	67	17	18	44	[illegible]
Coal mining 62			3	2	1		5	54			3	4	2		1	3	1	2			3	3	3			20	1		2	1	2		1	2	
Crude petroleum and natural gas 63																																			
SERVICES																																			
Federal government enterprises 64	9	2	3	17	34	4	19	40	3	5	16	4	19	2	13	4	3	10	5	5	6	3	3	5	4	52	5	5	17	12	11	3	2	5	
Transportation and warehousing 65	49	35	97	96	158	29	166	3405	38	67	150	87	92	17	108	29	45	77	45	25	54	37	60	26	38	566	66	41	81	37	191	21	70	75	[illegible]
State and local government enterprises 66			1	1	2	1	2	39	1	1	3	1	1		2		1	1	1		1		1	1	1	6	1	1	1	1	2			1	
Hotels, personal and repair services, except automobile 67	12	3	9	3	49	5	5	50	5	5		8	8	2	13	3	3	5	6	4	4	3	4	3	8	20	6	4	9	7	13	4	2	7	
Automobile repair and services 68	2	4	7	3	5	4	5	374	5		2	5	2	1	10	1	3	1	1	1	3	1	4	1	3	11	4	1	3		22	3	1	4	
Radio and television broadcasting 69																																			
Amusements 70					1			1																		1									
Medical and educational services, nonprofit organizations 71	5	2	5	8	22	3	9	85	3	6	15	5	8	1	8	2	3	5	5	3	3	3	4	2	5	31	5	3	7	4	11	2	3	5	
Wholesale and retail trade 72	112	108	242	103	672	140	234	3082	130	182	306	238	282	62	422	73	161	204	178	143	135	80	147	69	137	914	227	193	206	94	389	65	107	143	[illegible]
Finance and insurance 73	31	10	23	16	126	14	70	449	24	40	51	26	27	11	58	11	24	16	24	15	22	18	20	8	38	115	31	13	30	17	86	17	17	39	
Communications, except radio and television broadcasting 74	12	8	23	3	57	7	19	211	33	28	76	14	27	5	39	6	10	20	21	13	8	8	13	7	40	63	45	8	28	10	43	14	3	13	
Business services 75	117	20	73	356	179	19	1336	2126	41	68	59	43	185	22	164	117	29	413	70	77	89	34	57	44	51	763	59	41	76	36	122	22	26	45	[illegible]
Real estate and rental 76	38	22	53	10	216	32	75	386	33	28	97	23	49	14	105	27	38	25	47	23	18	13	23	15	85	84	35	29	53	71	66	31	11	41	
Maintenance and repair construction 77	1	1	3		11	1	2	310	3	10	30	2	11	1	21	1	4	3	1	2	2	1	1		10	94	6		9	3	10	9	1	3	
Research and development 78								7			16		3			3						16				16				3	3				
Office supplies 79	4	2	3	1	13	2	4	37	3	7	13	4	9	1	8	2	2	3	7	4	3	2	3	2	4	12	5	2	8	4	6	2	1	4	
Business travel, entertainment and gifts 80	29	21	38	14	127	21	63	459	47	124	70	52	146	19	91	21	31	46	108	70	29	30	44	28	57	129	66	39	143	72	93	23	10	50	
Scrap, used and secondhand goods 81						2			5		8	12	5		7			1		1	9	7	3	1	3	11	12	3	1		45	4			
Noncompetitive imports			1		11		17	1980	8						116				1						17				8	8					
Value added	1822	900	1821	3818	7345	705	3706	23968	1499	2172	8018	1928	3563	542	2967	1106	1017	1802	2202	1698	1244	1255	1837	871	2487	905	2182	1435	3384	1760	4139	1128	932	2168	[illegible]

DOLLAR-FLOW TABLE contains figures that show, in millions of dollars, the transactions among the 81 sectors of the economy that are required to sustain a gross national product of $600 billion, as set forth in table on page 32. Cells are left blank where the trans-

BASIC NONMETAL — ENERGY — SERVICES

36 ING · 37 ORES MINING · 38 STEEL MANUFACTURING · 39 AND FERROALLOY ORES MINING · 40 STONE AND CLAY PRODUCTS · 41 STONE AND CLAY MINING AND QUARRYING · 42 PRINTING AND PUBLISHING · 43 GLASS AND GLASS PRODUCTS · 44 PAPERBOARD CONTAINERS AND BOXES · 45 PAPER AND ALLIED PRODUCTS EXCEPT CONTAINERS · 46 WOODEN CONTAINERS · 47 LUMBER AND WOOD PRODUCTS EXCEPT CONTAINERS · 48 FORESTRY AND FISHERY PRODUCTS · 49 MISCELLANEOUS TEXTILE GOODS AND FLOOR COVERINGS · 50 RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS · 51 BROAD AND NARROW FABRICS, YARN AND THREAD MILLS · 52 PAINTS AND ALLIED PRODUCTS · 53 LEATHER TANNING AND INDUSTRIAL LEATHER PRODUCTS · 54 LIVESTOCK AND LIVESTOCK PRODUCTS · 55 MISCELLANEOUS AGRICULTURAL PRODUCTS · 56 AGRICULTURAL, FORESTRY AND FISHERY SERVICES · 57 PLASTICS AND SYNTHETIC MATERIALS · 58 CHEMICALS AND SELECTED CHEMICAL PRODUCTS · 59 CHEMICAL AND FERTILIZER MINERAL MINING · 60 PETROLEUM REFINING AND RELATED INDUSTRIES · 61 ELECTRICITY, GAS AND WATER · 62 COAL MINING · 63 CRUDE PETROLEUM AND NATURAL GAS · 64 FEDERAL GOVERNMENT ENTERPRISES · 65 TRANSPORTATION AND WAREHOUSING · 66 STATE AND LOCAL GOVERNMENT ENTERPRISES · 67 HOTELS, PERSONAL AND REPAIR SERVICES EXCEPT AUTOMOBILE · 68 AUTOMOBILE REPAIR AND SERVICES · 69 RADIO AND TELEVISION BROADCASTING · 70 AMUSEMENTS · 71 MEDICAL AND EDUCATIONAL SERVICES, NONPROFIT ORGANIZATIONS · 72 WHOLESALE AND RETAIL TRADE · 73 FINANCE AND INSURANCE · 74 COMMUNICATIONS EXCEPT RADIO AND TELEVISION BROADCASTING · 75 BUSINESS SERVICES · 76 REAL ESTATE AND RENTAL · 77 MAINTENANCE AND REPAIR CONSTRUCTION · 78 RESEARCH AND DEVELOPMENT · 79 OFFICE SUPPLIES · 80 BUSINESS TRAVEL, ENTERTAINMENT AND GIFTS · 81 SCRAP, USED AND SECONDHAND GOODS

36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	
						1		1	1		1		1	10			3	1	5									1	1		9			13	3	24	1		1	6				34	1	1
						7			2	1	4			1																	5					17				2	22					2
		2					7			4	25		8	1																	15					17				4						3
																																				4				3				189	2	4
7		20					4	4	9		14		9	24	22	1					3	7		4					6	2	129	2			51	69			6	34		2		9	8	5
3		3		5					32		2		16	4	45		2	10	46			39		2				3	20		173	24	3	7	46	52	41	7	29	4	1	3			2	6
13		47		62		8	4	8	28		12		1	8	31	27	30	36			60	201		66	1		1		15	4	236	12		1	781	159	15	1	37	36		31		42		7
1		9		8					102			33	21	2	31	79	276	3704	4	10	23	181		15	1			345	132	1	18				225	703				84		5		2610	1	8
3		33		8		47		18	38	2	17		2	7	84						7	154					12				1					37				14		5			27	9
2		2				7		2																												12				5		1413		6		10
		2		1		23							1	23								1							215							90				18		2066			24	11
8		21	3			1					9	27		3					4						2	15			398		12	13		1	26	17	13	7	24	9		8			4	12
11			2			7								6							1			6	5				23		13		47		15	85		162		15	29	498		49	76	13
1		3			30						5											8	4			15			18							18				6	11	4			3	14
18		16		25	1	44	3	5	13		17	3	25	41	22	2	1	1	1	1	3	24		9	8	5	1		63	1	344	2	12	116	43	147	30	13	329	19	65	14	270	56	23	15
1		2		1		67			4					3							13	7									141			33	96	48			255	6		42	14	16	1	16
3		2		1			1		1													1							3		53					47			114	17	29	14			9	17
5		3					1							4																	157					32				14	80	200		33		18
5	1	7		5		2	3		4					13							1	4		2			1		34		93	21			345	56				11	21	145		10	36	19
		2				6			2													9			11				3						4	59	6		639	10		16	9		12	20
		36					1						1					6	255																	24			181	8		16			8	21
	1	3	1																						3		20		107							15			136	6	1	65			3	22
	38	19	32	1	101	1																	19			133	52									37			24	10	28	5			9	23
66				1							1			1				9	28			1			1		2	1	96	1	5	156			16	65	3	6	6	5	7	31			6	24
96	1	171		12		2	4	3	11		2		1	6	3		1				7	11		3	3	13			31			1				20			25	46		137			9	25
19	1	48	1	2	8	3					1		1					30	45				2		1	8	12	12	116	16		1499			2	276			7	24		246			117	26
42	3	80		4	7	2	4	2	8		14			8	2						3	5	1	2		5	106		19							39				12	25	4			15	27
74	1	13	1	36		2	7	2	17	1	13		1	14	4		1	1	1		2	2		1	3	6	1		9		10	44				24				4	164	96				28
47	6	112	1	9	4	7	2	1	6					5	1		1				4	20	4	4	13	8	44		41		9	8				31		1		9	105	226			7	29
3				2		1								3													15		33		310					13		7		18		188				30
4	1	64	2	7			1		1		4			4	1	1					1	3		3		1	8		1							129				12	1175	20			28	31
45		192		5	1	1	2	1	5		4			24				2	4		2	6		1		1	1	1	9	1		139				30			1	11	1	3			31	32
								19	1							117		6	19		7	112		182												10				3		1			9	33
125	1	167		15		4	13	5	21	1	28			30	2	1	1	27			4	13	1	3		21	7		20						27	58				7	28	4			44	34
143	2	447	1	121	1	28	12	12	143	4	88	1	4	102	12	4	2	36	50	12	8	57	1	251	211	19	67	4	54	29	37	150			1	83		4	1	9	70	24	6	5	23	35
3959	9	425	2	20	2	20	6	1	19		13		1	17	3	1		1	1		2	234	2	3	11	22	10		64		9					21		32	21	15	375	17			70	36
1050	306	9	53	5	1																	75			4															7						37
158	68	5395	28	41	30			3	1	24			1	19	5	14						282	14	2	79	30	4		50	3						10				27	365	7	3		140	38
29	17	1396	84	12	1																	74	1	4				2												7						39
63	8	398	1	1222	135		83		65	1	43		3	32	3	25	11	1	33		2	49		46	32	8	5	16	5	1	69	52				159				26	731			3		40
6		73		662	16		33		47					8		1		1	87		1	26	12	80		2		1	2							5				11	175					41
12	1	38		21	1	2124	4	33	134	1	42		2	29	11	6	2	6	9		6	40		1	7	1	1	50	99	16	9	14	13	27	428	812	522	154	7259	76	2	1	1043	8	46	42
		2		8			142	9	1		13		3	59	31			4			2	24		3			1		7		4	129			8	141				8	109	1	1	3		43
9		20		97	4	84	222	150	369	1	48	13	20	67	113	27	2	17	3	8	31	94	1	43	1	2	1	9	11		25	1	3	1	27	467	32		11	12		2			24	44
37	1	64		221	18	2895	7	2088	2632	1	78	11	35	38	22	19	4			3	257	158	4	77	22	9	6	36	44	3	194	4	11	5	113	609	135		88	14	91	9	436	4		45
		4		15			16	3	7	22	27						3		131		1	4							23							122				3						46
14	2	26	8	18		1	44	4	877	221	3193			15	2	2		2	2		1	41		3	4	25	8		12		7				4	77				31	557			2		47
											1050	21					1					20							2											2				20		48
7		1		2		24			22		2	15	279	610	330			7	35	15	1	3					3		21	3	31	22	2	4	30	31	28	5	19	8	1	4				49
22	5	82	1	104	39	20	11	43	190	1	71	11	47	276	57	8	11	27	203	2	100	111	4	9	11	30	41	1	338	7	92	360	1	2	85	314	71	9	87	58	88	39	12	2	5	50
20	2			18		1			78				551	193	4894	1			9		5	1			3	2			9		167				3	12		1		22		1			71	51
10		20		12					4	1	50	3	2	2	5	4					35	57		8		1	7		52			81				30				14	1172					52
				1										7	2		169												4							3				1						53
												99	72	189	136		69	5236	2223	281								2	2					15	6					1187				36		54
				5							271	217	20		1562			8246	923	708		18						826	45						7					1803				88		55
											11	23						616	1145	2										1				4		203				7						56
150		6		112				15	123		75		533	1304	1221	306					152	319		20	3											5				14		11				57
130	55	246	17	215	23	241	111	11	444		80		10	428	221	574	84	43	1492		1937	3126	23	695	13	59	65		47	32	131				6	133			18	100	94	112	13			58
3	2	10		30	1		1		21					10	1		1		37		1	467	43	2					1											2						59
56	11	196	14	114	61	15	9	33	160	4	101	25	6	22	35	23	5	60	1171	3	74	876	7	1651	326	40	69	8	1996	54	191	36	3	5	93	965	124	23	144	433	500	26			9	60
288	39	614	22	284	52	73	106	24	251	5	73	1	22	94	156	11	9	114	225	2	54	383	32	349	4501	87	104	97	193	500	313	200	8	57	555	2541	166	80	327	331	33					61
16	2	675	6	84	4		4	1	98		2		2	13	21	1	3	7	1		31	81	1	13	727	628		62	35	105		14				6	8		40	14						62
																						32	2	12351	1553		320			27										161		1				63
6	1	21	1	9	1	118	8	4	15	1	4	1	4	8	11	6	6	5	4	1	26	36	1	42	523	4		8	73	5	9	5	1	4	21	1300	433	54	874	361						64
265	20	1309	32	598	19	248	68	159	488	21	512	9	66	197	339	73	27	645	351	14	172	481	21	1113	495	27	111	972	2768	93	120	98	3	30	159	526	312	23	150	518	397	3		3426	59	65
4	1	18		13	2	3	1	1	17		7		1	3	3	1		1	1		2	8		9	3400	1	6	1	970	1	25	29		2	16	475	93	5	10	554	3					66
10	1	29	1	15	2	23	5	6	13	2	21		4	12	23	1	2				4	10	1			1	1			10	471				146	298			162	348				1247		67
8		9		33	1	18	2	4	10	5	87		2	3	8	4	1	75	66		2	21		25	33	1	19	47	1078	6	154	176	2		65	1095	110	21	156	152	30					68
																																	6						2023	19						69
		1				1									1														33				400	1780	111	322	7	4	44	130		7		157		70
12	1	27	1	11	2	19	3	5	13	1	11	1	3	9	15	3	1	177	16	1	5	14	1	22	22	4	12		41		16	10	2	7	393	127	186	12	5	50	13	719		48		71
415	34	911	23	299	81	398	103	178	524	29	460	24	125	311	428	104	31	1139	1299	6	110	444	17	227	320	127	135	82	1320	56	692	889	24	94	558	2098	339	69	561	1421	1838	16		476		72
80	23	191	8	100	24	163	28	31	83	4	71	39	22	52	84	19	7	236	373	7	39	147	5	152	147	36	143	7	922	60	263	274	17	174	351	2095	7143	74	391	2748	66	7				73
37	3	91	2	35	4	214	9	11	40	1	29	4	8	28	23	10	4	66	93	8	15	71	1	31	62	3	3	15	357	33	86	73	82	42	253	1343	546	116	833	296	24	3				74
104	11	225	8	143	19	749	45	23	179	3	63	135	24	217	132	37	5	58	1035	6	71	210	5	468	300	18	455	74	654	91	420	204	83	286	760	6306	1359	228	729	1699	80	27				75
52	51	100	104	81	54	614	21	46	57	6	73	52	23	96	65	30	4	365	2338	21	33	161	8	184	74	81	1852	54	1345	95	752	411	104	382	2068	6695	2729	213	1191	1687	47	16				76
5	2	170	1	5	3	59	1	17	55		21		1	9	9	1		292	492	3	35	8		34	733	3	6	19	1641	1584	47	143	11	169	904	1028	159	410	29	7852	1					77
7		23					3		3						3						16	33		9				2							53											78
5		12		6	1	52	2	3	6		4	1	1	7	7	2		1	3		1	14		7	22	1	4	28	57	38	26	4	2	9	116	285	181	51	328	36	3					79
63	7	113	6	96	10	380	27	32	77	5	81	2	14	79	57	31	4	22	35	2	11	260	7	41	80	15	90	48	192	20	202	39	41	115	589	2122	487	63	285	75	50	22				80
	1	763	1	14	5		31		225		4		41	4							1	4	1	4		7	146				62	96				139					16					81
18				15		2					1		55	313	112	11	5	16	313			54						245	899					140	7	40	142	75								
4310	627	10211	578	4918	1242	7943	1628	1807	4852	216	3624	750	816	3975	3681	911	382	11294	15523	900	2243	6216	387	4797	13201	2139	8843	2376	27073	3460	9857	5045	1180	4005	20534	91513	19659	11070	14909	59513	13773	547				
36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60	61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80	81	

actions were less than $.5 million. Colored cells indicate the largest transactions. Each cell in bottom row ("Value added") indicates what the sector in whose column it appears contributes to gross national product above the sum of its inputs from other industries.

		1 Personal consumption expenditures	2 Investment (producers' durable equipment)	3 New construction	4 Net inventory change	5 Federal government purchases	6 State and local government purchases	7 Exports	8 Competitive imports	9 Total final demand	10 Gross domestic output
FINAL NONMETAL	FOOTWEAR AND OTHER LEATHER PRODUCTS 1	3469	8		42	29	4	50	21	3583	4133
	MISCELLANEOUS FURNITURE AND FIXTURES 2	173	1080	275		34	172	24		1757	2012
	HOUSEHOLD FURNITURE 3	3196	167	398	9	35	75	22		3884	4378
	TOBACCO MANUFACTURES 4	5684			32			585	36	6201	7916
	APPAREL 5	14880			173	58	115	192	45	15027	18994
	MISCELLANEOUS FABRICATED TEXTILE PRODUCTS 6	1482		1		140		25	11	1635	3054
	DRUGS; CLEANING AND TOILET PREPARATIONS 7	4982			72	179	243	440	60	5856	8829
	FOOD AND KINDRED PRODUCTS 8	60994		23	351	262	350	1489	1772	61697	84719
FINAL METAL	SPECIAL-INDUSTRY MACHINERY AND EQUIPMENT 9	27	1981		144	41	41	501	44	2404	3364
	ORDNANCE AND ACCESSORIES 10	212		7	113	3042	6	25	17	3388	6235
	AIRCRAFT AND PARTS 11	34	480		360	8722		754	80	9550	16979
	MISCELLANEOUS TRANSPORTATION EQUIPMENT 12	971	1591	3	102	880	51	403	80	3718	4992
	RADIO, TELEVISION AND COMMUNICATION EQUIPMENT 13	1821	1362	49	98	1881	82	269	56	5310	8042
	MATERIALS-HANDLING MACHINERY AND EQUIPMENT 14		479	335	30	185	67	104	20	1117	1458
	MISCELLANEOUS MANUFACTURING 15	3390	374	113	45	45	239	157	337	4025	7064
	OPTICAL, OPHTHALMIC AND PHOTOGRAPHIC EQUIPMENT 16	610	215		6	178	19	119	104	1043	2027
	SERVICE-INDUSTRY MACHINES 17	325	1261	263	48	86	27	179	7	2086	2974
	HOUSEHOLD APPLIANCES 18	3260	127	276	88	29		220	2	3823	4835
	SCIENTIFIC AND CONTROLLING INSTRUMENTS 19	473	722	257	10	746	118	251	155	2402	4690
	OFFICE, COMPUTING AND ACCOUNTING MACHINES 20	78	1365		18	100	118	182	59	1766	2959
	FARM MACHINERY AND EQUIPMENT 21	10	2283	3	32	7	25	256	172	2381	3303
	ENGINES AND TURBINES 22	170	783	3	81	324	3	288	9	1480	2962
	CONSTRUCTION, MINING AND OIL-FIELD MACHINERY 23		1791	229	100	109	29	962	1	3018	4162
	MISCELLANEOUS ELECTRICAL MACHINERY, EQUIPMENT AND SUPPLIES 24	347	113	20	34	121	44	96	29	679	2039
	METALWORKING MACHINERY AND EQUIPMENT 25	39	1562	1	179	233	5	446	51	2057	4863
	MOTOR VEHICLES AND EQUIPMENT 26	12262	4793	2	726	409	599	1230	863	17706	30346
	GENERAL INDUSTRIAL MACHINERY AND EQUIPMENT 27		1411	366	111	267	5	368	13	2292	5003
	ELECTRIC-LIGHTING AND WIRING EQUIPMENT 28	420	34	1067	41	25	13	87	15	1590	3062
	ELECTRIC INDUSTRIAL EQUIPMENT AND APPARATUS 29	21	2156	569	179	241	7	372	77	3108	6802
	ELECTRONIC COMPONENTS AND ACCESSORIES 30	198	36	3	64	313		121	2	605	3539
BASIC METAL	HEATING, PLUMBING AND STRUCTURAL-METAL PRODUCTS 31	97	957	6966	98			305	27	8200	10756
	MACHINE-SHOP PRODUCTS 32			3	15	57	48	20	23	89	2102
	METAL CONTAINERS 33		14		17	23		34	1	88	2776
	STAMPINGS, SCREW-MACHINE PRODUCTS AND BOLTS 34	335		118	91	126	5	40	37	496	4898
	OTHER FABRICATED METAL PRODUCTS 35	509	221	1166	62	150	62	336	145	2237	8574
	PRIMARY NONFERROUS METAL MANUFACTURING 36	14		1166	14	448		408	1236	786	12189
	NONFERROUS METAL ORES MINING 37				44	263		6	393	167	1365
	PRIMARY IRON AND STEEL MANUFACTURING 38	26		2986	209	156		730	387	3302	25448
	IRON AND FERROALLOY ORES MINING 39				30			56	612	587	1046
BASIC NONMETAL	STONE AND CLAY PRODUCTS 40	285		5480	41	10		133	138	5812	10044
	STONE AND CLAY MINING AND QUARRYING 41	24		839	4	13	15	31	159	737	2012
	PRINTING AND PUBLISHING 42	3267		10	17	119	239	119	54	3717	16771
	GLASS AND GLASS PRODUCTS 43	172		114	6	3		91	84	291	2853
	PAPERBOARD CONTAINERS AND BOXES 44	48				5		24	5	72	4825
	PAPER AND ALLIED PRODUCTS, EXCEPT CONTAINERS 45	1139		434		99	14	340	1338	688	12643
	WOODEN CONTAINERS 46				13	2	1	4	8	14	588
	LUMBER AND WOOD PRODUCTS, EXCEPT CONTAINERS 47	203	11	4401	80	11		148	697	4135	10577
	FORESTRY AND FISHERY PRODUCTS 48	377			26	184		41	412	152	1522
	MISCELLANEOUS TEXTILE GOODS AND FLOOR COVERINGS 49	1008	62	5	38	7		62	440	665	2907
	RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS 50	1735	74	417	46	156	101	285	45	2678	9100
	BROAD AND NARROW FABRICS, YARN AND THREAD MILLS 51	944			147	73	15	278	345	818	14093
	PAINTS AND ALLIED PRODUCTS 52	22		264	5	3		38	2	319	2497
	LEATHER TANNING AND INDUSTRIAL LEATHER PRODUCTS 53				4			39	50	16	1173
	LIVESTOCK AND LIVESTOCK PRODUCTS 54	2806			813			35	315	3340	32653
	MISCELLANEOUS AGRICULTURAL PRODUCTS 55	3273		318	566	1474	31	2357	479	7541	30133
	AGRICULTURAL, FORESTRY AND FISHERY SERVICES 56				28	62	94	4			2016
	PLASTICS AND SYNTHETIC MATERIALS 57	11			58	6		456	54	361	5630
	CHEMICALS AND SELECTED CHEMICAL PRODUCTS 58	291		492	33	991	326	912	459	2520	15652
	CHEMICAL AND FERTILIZER MINERAL MINING 59	1			1	13	15	69	108	11	632
ENERGY	PETROLEUM REFINING AND RELATED INDUSTRIES 60	9696		1323	243	968	509	873	892	12236	23054
	ELECTRICITY, GAS AND WATER 61	10751		201		463	655	55	49	12076	26968
	COAL MINING 62	348			30		81	447	4	842	3665
	CRUDE PETROLEUM AND NATURAL GAS 63				58			44	1612	1627	12817
SERVICES	FEDERAL GOVERNMENT ENTERPRISES 64	836				77	88	82		1082	5454
	TRANSPORTATION AND WAREHOUSING 65	11233	669	2425	178	1869	535	2987	24	19920	43749
	STATE AND LOCAL GOVERNMENT ENTERPRISES 66	414		18		154	6	6		599	6357
	HOTELS; PERSONAL AND REPAIR SERVICES, EXCEPT AUTOMOBILE 67	12598				326	114			13039	16208
	AUTOMOBILE REPAIR AND SERVICES 68	5818		354		169	106			6447	10481
	RADIO AND TELEVISION BROADCASTING 69							13		13	2060
	AMUSEMENTS 70	4377			30	23	61	350		4719	7529
	MEDICAL AND EDUCATIONAL SERVICES; NONPROFIT ORGANIZATIONS 71	27157		78		152	425			27812	30150
	WHOLESALE AND RETAIL TRADE 72	81465	4958	6657	127	888	254	1907	860	97116	126318
	FINANCE AND INSURANCE 73	15645		584			248	35	62	16573	35078
	COMMUNICATIONS, EXCEPT RADIO AND TELEVISION BROADCASTING 74	5737	536	146		247	275	96		7036	13000
	BUSINESS SERVICES 75	2499		3427		751	752	229		7658	32506
	REAL ESTATE AND RENTAL 76	53230	1664	281		166	333	333		56007	82399
	MAINTENANCE AND REPAIR CONSTRUCTION 77			9		1430	4525			5964	22493
	RESEARCH AND DEVELOPMENT 78					6910				6910	7126
	OFFICE SUPPLIES 79			19		98	173			290	1806
	BUSINESS TRAVEL, ENTERTAINMENT AND GIFTS 80			302					218	84	8577
	SCRAP, USED AND SECONDHAND GOODS 81	18	1080	98	269	154	450	275	404	758	961
	NONCOMPETITIVE IMPORTS	5207	28		14	3695		263	13639	4433	
	VALUE ADDED	6218		24959	422	26036	25572	5798	896	87 5	600000
		389358	34285	70321	2022	67359	38245	31410	28955	600000	

FINAL DEMAND on industry is listed in this table. Ninth column gives totals for deliveries to final-demand sectors; 10th lists each industry's output. The total of the "Total final demand" column is gross national product of $600 billion. Colored figures are negative.

the U.S. economy. In particular its reception by the business community, now equipped with computers of sufficient capacity to make use of the technique, indicates that future ventures in this field by Government agencies will have more generous backing and encouragement.

To visualize the economy as it is revealed by input-output analysis it is easiest to begin with a table of dollar flows, the third of the three interindustry tables that illustrate this article [*see preceding two pages*]. This table shows the dollar flows corresponding to a gross national product of $600 billion, a bench mark first surpassed by the economy in 1964. The makeup of this hypothetical gross national product is detailed by industry and by category of ultimate market or final demand in the table at the left. From this bill of goods the table of interindustry dollar flows was computed, purely for purposes of demonstration, in accordance with the specifications for the economy set out in the Department of Commerce input-output table for the year 1958 (when the gross national product was $445 billion). The cells in each horizontal row of the table show the distribution of the outputs—the sales—of that industry or sector to each of the 81 industrial sectors. The sum of these outputs plus the industry's deliveries to final demand equals its total output—the conventional index of the activity of an industry—which is shown in the column at the far right in the table at the left.

As every sale is a purchase, so each figure in a horizontal row is also a figure in a vertical column: each output from one industry is shown to be an input to another. The figures in each vertical column accordingly list the inputs to that industry or sector from all the others. In the "Value added" row at the bottom of the table the entry for the industry in question totals up its wage bill, depreciation, profit and other "prime factor" charges. These constitute the industry's own contribution to the gross national product above the value of the inputs it draws from other industries or sectors. The value added plus the total of the intermediate inputs (including the entry in the "Imports" row) equal the total output of the industry, as entered in the total-output ("Gross domestic output") column in the table at the left. The rows and columns—that is, the outputs and inputs, or sales and purchases, making up the total activity of the economy—thus come into balance in the double-entry bookkeeping of input-output economics.

The dollar-flow table also shows the national accounts in balance. The sum of all the entries in the value-added row is equal to the sum of all the entries in the "Total final demand" column in the table on the opposite page. This figure is the gross national product. As the final-demand columns show, "gross national product" expresses the total activity of the economy in terms of the expenditures by which goods and services are acquired for final use by consumers and the Government and for investment and exports.

Here it should be noted that no total is given at the foot of the total-output column in the same table. That is because this figure—$1,032 billion—is misleading as an index of economic activity. It compounds all the intermediate transactions through which goods or services reach their final destination in the marketplace; it redundantly adds, for example, to the consumer's outlay for fabricated steel in an automobile ("Personal consumption expenditures," row 26 in the table) the price paid by the motor vehicles and equipment industry for the same metal in the raw sheet (column 26, row 38 in the dollar-flow table on pages 30 and 31) and again the price paid by the primary iron and steel manufacturing industry for the same metal in the ore (column 38, row 39). The consumer, of course, pays only once for the metal in the ore and for each unit of value added between the mine and the showroom. In accounting for these interindustry transactions, each of which is reckoned in the total output of the industry in question, and relating these transactions to final demand, input-output analysis yields its deep insights into the structure and operation of the economy.

The figures in the dollar-flow table were computed from the quite different set of figures shown in the table on pages 26 and 27. These are the input-output coefficients on which the technique of input-output analysis turns. The figure in each cell expresses the ratio of the input from the industry in whose row the cell appears to the total output of the industry in whose column the cell appears. Although the dollar-flow figures in the table on pages 30 and 31 are hypothetical, the input-output coefficients reflect the real activity of the U.S. economy in the year 1958, as analyzed by the Office of Business Economics. In the present table the coefficients from the Office of Business Economics table have been recomputed by the Harvard Economic Research Project in order to show gross domestic output. Competitive imports are therefore entered as negative figures in final demand, whereas noncompetitive imports are entered in an external row at the bottom of the table and represent tropical agricultural products such as coffee and certain minerals. It should be noted also that sectors 78 through 81 are "dummy" industries, set up to simplify the estimating procedures.

As can be imagined, the construction of this table has involved a considerable enterprise in fact-gathering. Actual records of interindustry transactions had to be searched out and compiled, and these studies were supplemented and refined by reference to the technological considerations underlying the transactions. Although the coefficients in the table can be read as dollar figures (the sum of all the coefficients in a column plus the coefficient in the value-added row comes to $1,000.00), they are better visualized as standing for the input of the actual physical quantity of this or that commodity purchasable at the price (in 1958 dollars) shown and required to produce $1,000 worth of the output of the industry in whose column it appears. For each sector of the economy the column of input-output coefficients specifies the mix and proportion of inputs required to produce each unit of output. For the economy as a whole an input-output table reveals the structure of interlocking interdependencies that ties the highly differentiated and specialized parts of the system together as a whole. It presents, in effect, a working model of the system. As such it can be employed for the experimental study of a great many theoretical and practical questions about the economy.

The computation of the table of transactions for a $600 billion gross national product illustrates one such use. Input-output analysis derives its conceptual framework from recognition of the fact that all the possible interconnections of the different sectors of a national economy can be regarded as special instances of the general solution of a single large system of equations in matrix algebra. In the case of the 1958 table the system contains 81 equations, each corresponding to an industry or a sector and each involving 81 distinct but interdependent variables. The parameters of these variables, the constants of the equations, are the input-output coefficients. The coefficients answer the question "In what proportions?" To solve the equations for $600 billion—that is, to answer the question "How much?"—the first step was to set up the appropriate bill of final demand. With these numbers given, solution of the equations produced the dollar-flow table and the total outputs required of each industry. The task of computation is of course immense. Each unit of output from industry *A* requires inputs from industries *B*, *C*, *D* and so on; these inputs ultimately call for an increase in output from industry *A*, which itself turns out to be a supplier to *B*, *C*, *D* or a supplier to their suppliers, and so the flow of direct and indirect demand cascades again. Nonetheless, the solution of the 81 equations with their 81 variables, carried out to five significant figures, required only three minutes on the IBM 7090 computer at Harvard University.

The dollar flows and total outputs thus satisfy not only the final demand laid directly on each sector but also the demand laid indirectly on each sector by the final demand for the output of the sectors to which it delivers inputs and still other sectors to which its customers deliver inputs. In the case of the rubber industry (row 50), for example, the total output depends not alone on the direct demand for the industry's products arising from consumer and Government expenditures and from exports but on the indirect demand for rubber set up by the final demand for motor vehicles and equipment (column 26), for footwear and other leather products (column 1) and for transportation and warehousing (column 65). At a $600 billion gross national product, the total final demand for rubber is $2,678 million, but the total output of the industry is shown to be $9,100 million. Most of the rubber industry's output reaches final demand via inputs from rubber to other industries. A table of input-output coefficients can thus be used to forecast the total output required of an industry by changes in the size or composition of the gross national product.

An input-output matrix of another kind appears on pages 28 and 29. The figures in this matrix represent the general solution (by "inversion") of the input-output coefficient matrix. Each of these "inverse" coefficients expresses for the industry in whose row the cell appears that portion of the industry's total output required directly and indirectly to meet one unit of final demand for the product of the industry in whose column the cell appears. An inverse matrix facilitates many calculations that can be carried through without the mediation of a computer. Multiplication of the final consumer demand for automobiles ($12,262 million), for instance, by the inverse coefficient (.0129) appearing in the cell at the intersection of the automotive-industry column (column 26) and the iron-ore-industry row (row 39) yields $158 million. The figure expresses the direct and indirect demand for iron ore generated by the sale of $12,262 million worth of automobiles to consumers. Because the automotive industry buys no ore directly, however, the cell shows no entry at all in the table of input-output coefficients or in the table of dollar flows.

With the help of a table that embodied a more detailed analysis of the system, indirect relations of a still more remote order might be resolved. How would the demand for sulfuric acid be affected, for example, by a given increase in public expenditure for primary education? The demonstrated interdependence of the elements in the economic system suggests that such an effect may be of significance to some producers in the chemical industry. A rise in school budgets will increase the sale of elementary textbooks, which in turn means an increased demand for printing stock. The paper manufacturers' response to this demand will require an increase in the output of the wood-pulp industry, and the chemical industry will accordingly experience a step-up in the demand for sulfuric acid. The relatively coarse aggregation of the system in the present table, however, buries education in the "State and local government purchases" column in final demand and lumps sulfuric acid along with other chemicals in an undifferentiated chemical industry in sector 58.

In the tables illustrating this article the 81 industrial sectors have been "triangulated"; that is, they have been arranged in accordance with the hierarchy of interindustry dependence. The coloring of the cells in the table of input-output coefficients on pages 26 and 27 brings the structure into graphic relief. Here the color distinguishes those cells in which the input-output coefficient exceeds 1/81, that is, the cells to which the input exceeds $12.35 per $1,000 of output from the sector in whose column the cell appears. In

		FOOTWEAR AND OTHER LEATHER PRODUCTS 1	HOUSEHOLD FURNITURE 3	ORDNANCE AND ACCESSORIES 10	MISCELLANEOUS MANUFACTURING 15	HOUSEHOLD APPLIANCES 18	MOTOR VEHICLES AND EQUIPMENT 26	RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS 50	TRANSPORTATION AND WAREHOUSING 65	AUTOMOBILE REPAIR AND SERVICES 68	WHOLESALE AND RETAIL TRADE	EX
FOOTWEAR AND OTHER LEATHER PRODUCTS	1											
	3											
	10											
	15											
	18											
	26											
RUBBER AND MISCELLANEOUS PLASTICS PRODUCTS	50	245	177	151	252	158	870	276	338	360		
	65											
	68											
	72											

INTERINDUSTRY TRANSACTIONS between the rubber industry (subsumed under "Rubber and miscellaneous plastics products") and nine other sectors of the economy are excerpted from the dollar-flow input-output table. Such transactions account for most of the activity of the rubber industry. The gross domestic output of the rubber industry is given (*column at right*) as $9,100 million. The value of rubber delivered to total final demand is only $2,678 million. The difference between the figures is the amount of rubber sold to other industries. Each of these other industries somehow uses rubber and then in turn makes deliveries to still other

			MOTOR VEHICLES AND EQUIPMENT 26		PRIMARY IRON AND STEEL MANUFACTURING 38	IRON AND FERROALLOY ORES MINING 39	
MOTOR VEHICLES AND EQUIPMENT	26						
PRIMARY IRON AND STEEL MANUFACTURING	38		2664 2088				
IRON AND FERROALLOY ORES MINING	39		0129		1396		

INDIRECT ECONOMIC RELATION between iron ore and automobiles is illustrated in excerpts from the dollar-flow table and the inverse table. The steel industry ("Primary iron and steel manufacturing") buys iron ore from sector called "Iron and ferroalloy ores mining" and sells it to the automobile industry ("Motor vehicles and equipment"). This process is summarized in cells at any one column, therefore, the colored cells identify the principal suppliers to that industry. As can be seen, most of the colored cells fall on or below the diagonal line running from the upper left to the lower right corner. (The cells on the diagonal show the intramural transactions of each of the 81 industrial sectors.) The distribution of colored cells indicates that the sectors in the upper rows of the table deliver little of their output to other industrial sectors and so deliver most of it directly to one or another final-demand column. In contrast, the output of the sectors toward the bottom of the table is distributed primarily as inputs to other industrial sectors. The colored cells tend to cluster, moreover, in the blocks of intersecting rows and columns set off from one another by the heavier horizontal and vertical lines that mark

SALE 72	PERSONAL CONSUMPTION EXPENDITURES	FEDERAL GOVERNMENT PURCHASES	TOTAL FINAL DEMAND	GROSS DOMESTIC OUTPUT
	3469		3583	4133
	3196		3884	4378
		3042	3388	6235
	3390		4025	7064
	3260		3823	4835
	12262		17706	30346
314	1735		2678	9100
	11233		19920	43749
	5818		6447	10481
	81465		97116	126318

industries or to final demand. Whether an industry delivers to final demand or to other industries depends on the nature of its product. Footwear, for example, unlike rubber, delivers primarily to final demand.

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intersections of the three sectors. Only an inverse coefficient appears in the cell at the intersection of ore and automobiles.

the major categories of industry. In general, the sectors above and below any given row in the table bear quite different relations to that industrial sector: those above are its customers; those below are its suppliers.

Such triangulation of an input-output table not only serves to develop graphically the structure of the system but also facilitates the use of the table in forecasting and planning. Computation of the indirect effects of an increase in final demand for the output of a given industry, for example, requires principally the use of the coefficients for the inputs from the industries below it in the table. Correspondingly the computation of effects on this sector exerted by demand originating elsewhere in the system involves mainly the coefficients of its deliveries to its customers in the rows above.

The sectors in the inverse and dollar-flow tables are triangulated in the same order, but the cells in these two tables are colored to highlight the structure of the system from two different points of vantage. In the inverse table the coloring of the cells in each row distinguishes the principal industrial customers of the industry in whose row the cells appear, that is, the customers to which the industry delivers 1/81 or more of its total output. This might be described as the sales managers' view of the system. In the dollar-flow table the color identifies the 645 cells (roughly the same number of cells as in the two other tables) that show interindustry transactions of $100 million or more. Correspondingly this could be described as an economic analysts' view of the system.

During the 25 years since the publication of the first officially sponsored input-output table for the U.S. economy, many other countries—developed and underdeveloped, free-enterprise and centrally planned—have constructed tables for their systems. At three international congresses on input-output analysis, the last held under the auspices of the United Nations Secretariat in Geneva in 1962, planners from socialist countries and business economists from the West have found that they have a common language for discussion not only of theory but also of concrete experience in the solution of practical problems of many kinds. Last fall, simultaneously with the release of the 1958 table for the U.S., the statistical office of the Common Market countries published a set of statistically compatible tables for France, Belgium, West Germany, Italy and Holland; the construction of an integrated table for the entire western European economic complex will soon follow. At the other end of the scale an increasing number of smaller economic units—many states in the U.S. and even cities and metropolitan areas—have been compiling their own input-output tables. Managements of a number of large industrial enterprises, in the U.S. and abroad, have constructed input-output tables of their companies in order to gain better control of the effects that follow from the mutual interdependence of their many departments and of the phases in their production processes. In West Germany and France these internal corporate tables are coupled to the tables for the national economy in the storage memory of the computers in which they are put to work.

Further development of input-output analysis and the realization of its potentialities for informed and rational decision-making at all levels of economic life call for detailed and more up-to-date tables. Comparison of the 1947 and 1958 input-output tables for the U.S. economy indicates significant changes in the input-output coefficients arising from technological innovation. Change in a single input-output coefficient means change in the structure of the equation in which it appears; this forces a new solution of all the equations in a table and brings about change in all the elements of the inverse matrix. Even if the bill of final demand remains the same, therefore, this revises the dollar flows throughout the table and the total outputs of all the industries, although to a lesser degree in those more remote in the order of triangulation. These effects of change in coefficients suggest an important use of input-output analysis, which is to assess the consequences of critical advances in technology. With sufficiently detailed and current data at hand it would be possible to reckon with these results in advance.

Work has now begun on the preparation of an input-output table for the U.S. economy based on the data from the census of manufactures for 1963. It is to be hoped that this table will be designed to describe the steadily increasing complexity of the system in terms of at least 500 to 600 sectors. Such an input-output table would give the discipline of economics the 200-inch telescope it requires for its work today.

The Control of Biochemical Reactions

The cell is a factory and enzymes are its machines. Two feedback systems control production, one regulating synthesis of enzymes, another their activity. Models of the two systems are described

by Jean-Pierre Changeux

The analogy between a living organism and a machine holds true to a remarkable extent at all levels at which it is investigated. To be sure, living things are machines with exceptional powers, set apart from other machines by their ability to adapt to the environment and to reproduce themselves. Yet in all their functions they seem to obey mechanistic laws. An organism can be compared to an automatic factory. Its various structures work in unison, not independently; they respond quantitatively to given commands or stimuli; the system regulates itself by means of automatic controls consisting of specific feedback circuits.

These principles have long been recognized in the behavior of living organisms at the physiological level. In response to the tissues' need for more oxygen during exercise the heart speeds up its pumping of blood; in response to a rise in the blood-sugar level the pancreas increases its secretion of insulin. Now analogous systems have been discovered at work within the living cell. The new findings of molecular biology show that the cell is a mechanical microcosm: a chemical machine in which the various structures are interdependent and controlled by feedback systems quite similar to the systems devised by engineers who specialize in control theory. In this article we shall survey the experimental findings and hypotheses that have developed from the viewpoint that the cell is a self-regulating machine.

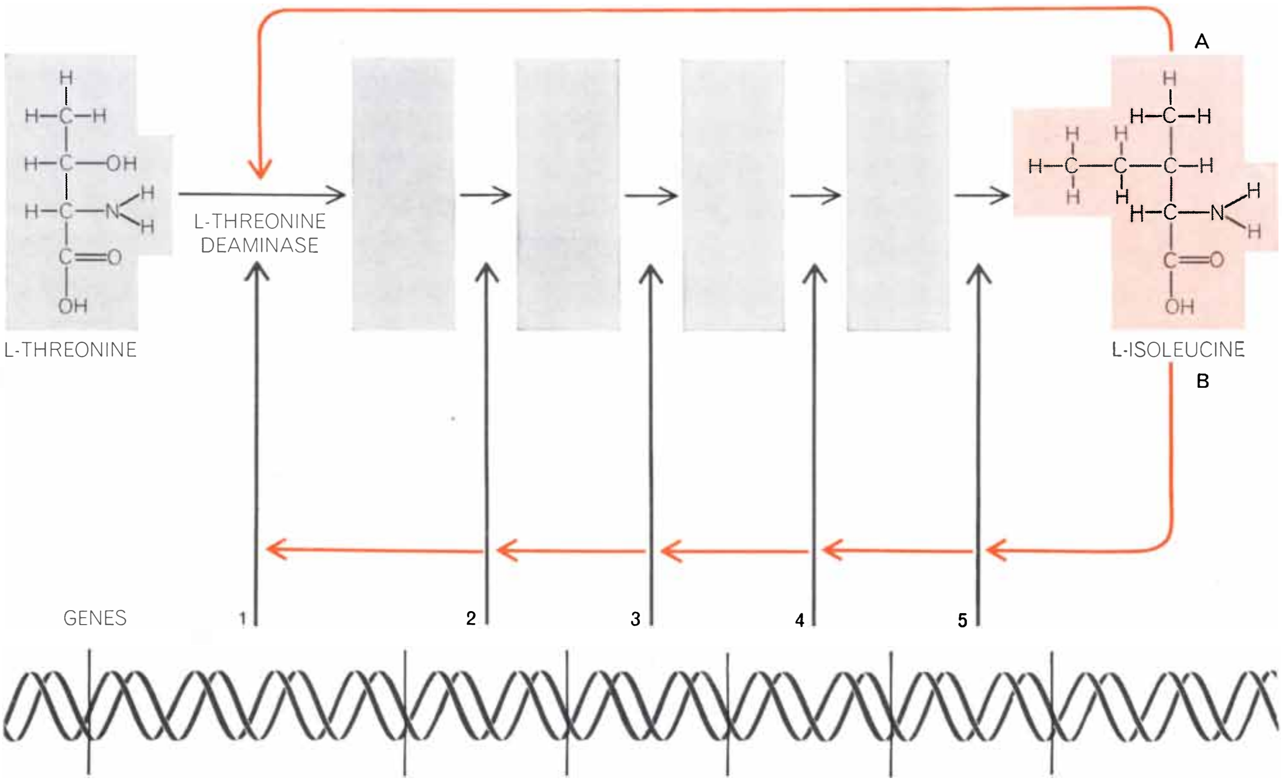
We can think of the cell as a completely automatic chemical factory designed to make the most economical use of the energy available to it. It manufactures certain products—for example proteins—by means of series of reactions that constitute its production lines, and most of the energy goes to power these processes. Regulating the production lines are control circuits that themselves require very little energy. Typically they consist of small, mobile molecules that act as "signals" and large molecules that act as "receptors" and translate the signals into biological activity.

The elementary machines of the cellular factory are the biological catalysts known as enzymes. The synthesis of any product (for example a specific protein) entails a series of steps, each of which calls for a specific enzyme. Obviously there are two possible ways in which the cell can control its output of a given product: (1) it may change the number of machines (enzyme molecules) available for some step in the chain or (2) it may change their rate of operation. Therefore in order to reduce the output of the product in question the cell may cut down the number of enzyme molecules or inhibit some of them or do both.

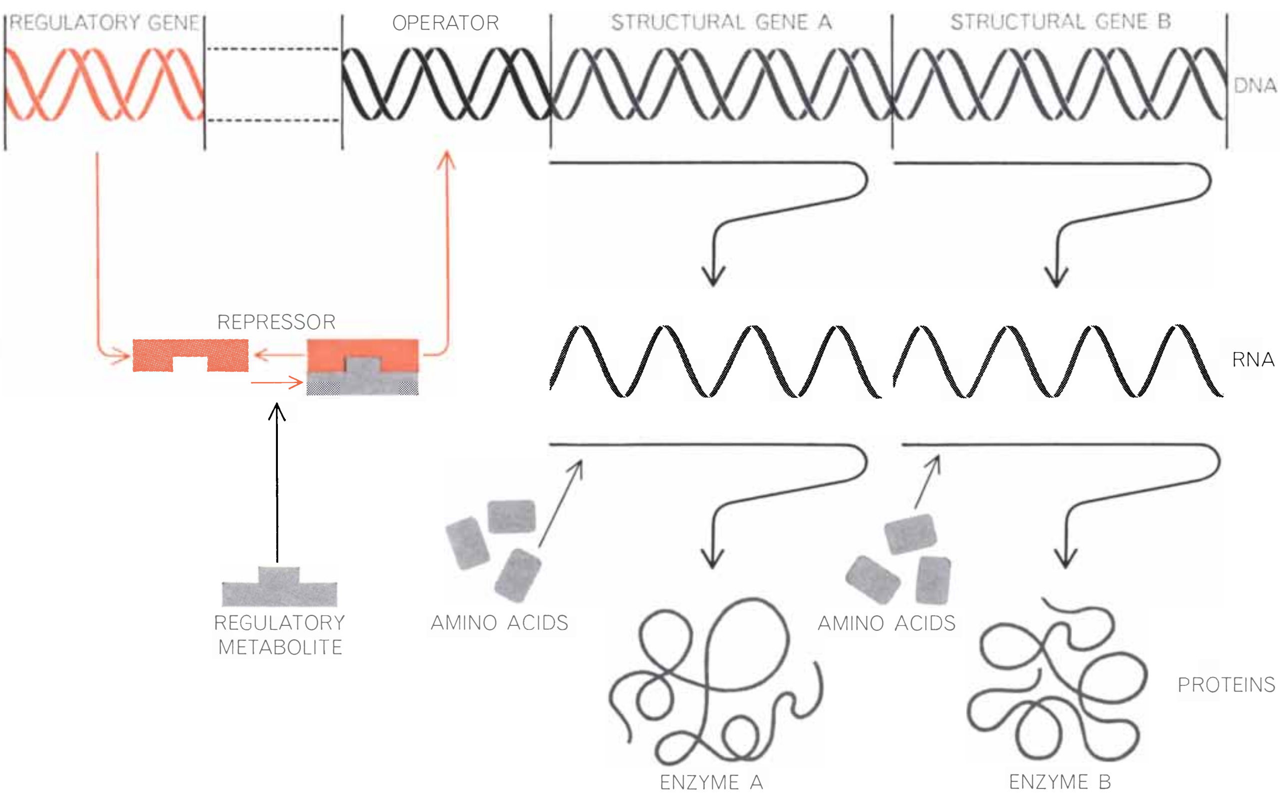
An excellent demonstration of such control has been obtained in experiments with the common bacterium *Escherichia coli*. The experiments involved the bacterial cell's production of the amino acid L-isoleucine, which it uses, along with other amino acids, to make proteins. Would the cell go on synthesizing this amino acid if it already had more than it needed for building proteins? L-isoleucine labeled with radioactive atoms was added to the medium in which the bacteria were growing; the experiments showed that when the substance was present in excess, the bacteria ceased to produce it. The amount of the amino acid in the cell in this case serves as the signal controlling its synthesis: if the amount is below a certain level, the cell produces more L-isoleucine; if it rises above that level, the cell stops producing L-isoleucine. Like the temperature level in a house with a thermostatically regulated heating system, the level of L-isoleucine in the cell exerts negative-feedback control on its own production.

How is the control carried out? H. Edwin Umbarger and his colleagues, working in the laboratory of the Long Island Biological Association, found that the presence of an excess of L-isoleucine has two effects on the cell: it inhibits the activity of the enzyme (L-threonine deaminase) needed for the first step in the chain of synthesizing reactions, and it stops production by the cell of all the enzymes (including L-threonine deaminase) required for L-isoleucine synthesis. Curiously it turned out that the two control mechanisms are independent of each other. By experiments with mutant strains of *E. coli* it was found that one mutation deprived the cell of the ability represented by the inhibition of L-threonine deaminase by L-isoleucine; another mutation deprived it of the ability to halt production of the entire set of enzymes. The two mutations were located at different places on the bacterial chromosome. Therefore it is clear that the two control mechanisms are completely separate.

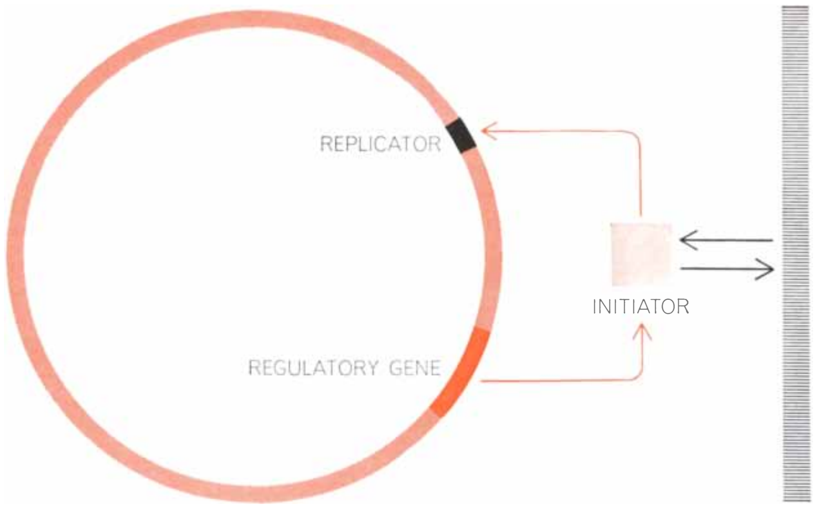
Let us first examine the type of mechanism that controls the manufacture of enzymes. It was Jacques Monod and Germaine Cohen-Bazire of the Pasteur Institute in Paris who discovered the phenomenon of repression: the inhibition of enzyme synthesis by the presence of the product, the product serving as a signal that the enzymes are not needed. The signal substance



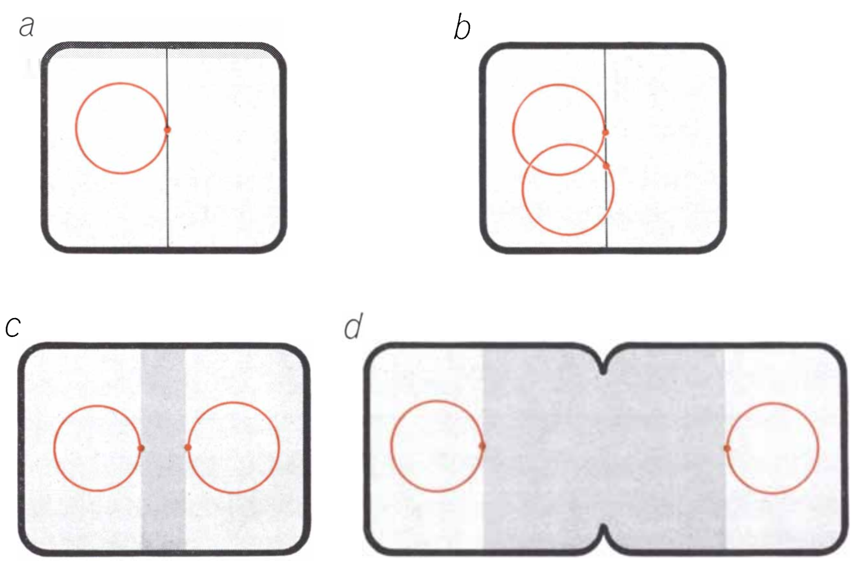
TWO FEEDBACK SYSTEMS control the biosynthesis of cell products, as shown here for the synthesis of the amino acid L-isoleucine in the bacterium *Escherichia coli*. The end product of the synthesizing chain acts as a regulatory signal that inhibits the activity of the first enzyme in the chain, L-threonine deaminase (*A*), and also represses the synthesis of all the enzymes (*B*).



CONTROL OF PROTEIN SYNTHESIS by a genetic "repressor" was proposed by François Jacob and Jacques Monod. A regulatory gene directs the synthesis of a molecule, the repressor, that binds a metabolite acting as a regulatory signal. This binding either activates or inactivates the repressor, depending on whether the system is "repressible" or "inducible." In its active state the repressor binds the genetic "operator," thereby causing it to switch off the structural genes that direct the synthesis of the enzymes.



REPLICATION OF DNA of a bacterial chromosome may be under a control like that of protein synthesis. A regulatory gene directs the synthesis of an "initiator," which receives a signal (perhaps from the cell membrane) that makes it act on the "replicator."



ROLE OF CELL MEMBRANE in replication is suggested by the fact that a bacterial chromosome is attached to a point on the membrane (*a*). It could be a signal from the membrane that initiates the formation of daughter chromosomes (*b*). Then the membrane begins to grow, separating the points of attachment (*c*) until the cell is ready to divide (*d*).

in their experiments was the amino acid tryptophan. They found that when the medium in which *E. coli* cells were growing contained an abundance of tryptophan, the cells stopped producing tryptophan synthetase, the enzyme required for the synthesis of the amino acid. This efficient behavior has since been demonstrated in many cells, not only bacteria but also the cells of higher organisms. The addition of an essential product to the cells' growth medium results in a negative-feedback signal that causes them to stop synthesizing enzymes they do not need.

In other systems the response of the cell is not negative but positive. We have been considering signals that repress the synthesis of enzymes; the cell can also respond to signals calling on it to produce enzymes. An example of such a situation is that the cell is confronted with a compound it must break down into substances it requires for growth.

The "induction" of enzyme synthesis in cells was discovered at the turn of the century by Frédéric Dienert of the Agronomical Institute in France. He was studying the effect of a yeast (*Saccharomyces ludwigii*) in fermenting the milk sugar lactose. He found that strains of the yeast that had been grown for several generations in a medium containing lactose would begin to work on the sugar immediately, causing it to start fermenting within an hour. These cells had a high level of lactase, an enzyme that specifically breaks down lactose. Yeast cells that had not been grown in lactose lacked this enzyme, and not surprisingly they failed to ferment lactose on being introduced to the sugar. After 14 hours, however, fermentation of the sugar did get under way; it developed that the presence of the lactose had induced the yeast to produce the enzyme lactase. The adaptation was quite specific: only lactose caused the yeast to synthesize this enzyme; other sugars failed to do so.

In recent years Monod and François Jacob of the Pasteur Institute have worked out some of the basic mechanisms of enzymatic adaptation by the cell, in both the repression and induction aspects. First they discovered that a single mutation in *E. coli* could eliminate the control of lactase synthesis by lactose: the mutant cells produced lactase just as well in the absence of lactose as in its presence. In these cells only the triggering effect was changed; the enzyme they produced was exactly the same as that synthesized by nonmutant strains. In other words, it appeared that the rate of production of the enzyme was controlled by one gene and that the structure of the enzyme was determined by quite another gene. This was confirmed by genetic experiments that showed that the "regulatory gene" and the "structural gene" were indeed in separate positions on the bacterial chromosome.

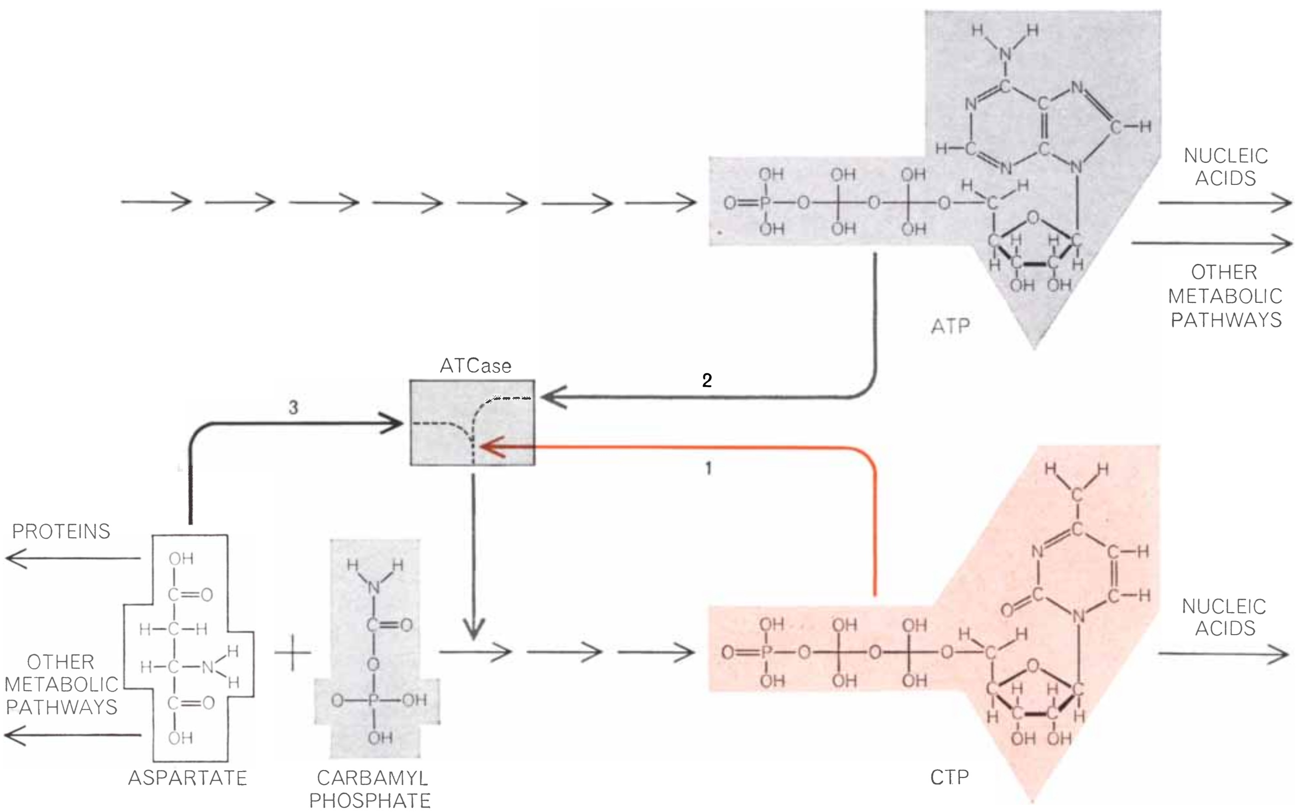
How does the regulatory gene work? Arthur B. Pardee, Jacob and Monod found that it causes the cell to produce a "repressor" molecule that controls the functioning of the structural gene. In the absence of lactose the repressor molecule prevents the structural gene from directing the synthesis of lactase molecules. The repressor does not act on the structural gene directly; it binds itself to a special structure that is closely linked on the chromosome with the structural gene for the enzyme and with several other genes involved in lactose metabolism. This special genetic structure is called an "operator." The binding of the repressor to the operator causes the latter to switch off the activity of the adjacent structural genes, and in this way it blocks the complex series of events that would lead to synthesis of the enzyme.

Jacob and Monod have shown that this scheme of control applies to any category of "adaptive" enzymes [*see bottom illustration on page 37*]. The repression and induction of enzymes can be regarded as opposite sides of the same coin. In a repressible system the binding of the regulatory signal on the repressor activates the repressor so that it blocks the synthesis of the enzyme. In an inducible system, on the other hand, the binding of the inducing signal on the repressor *inactivates* the repressor, thus releasing the cell machinery to synthesize the enzyme. Mutant cells that lose the repressive machinery need no inducer: they synthesize the enzyme almost limitlessly without requiring any induction signal.

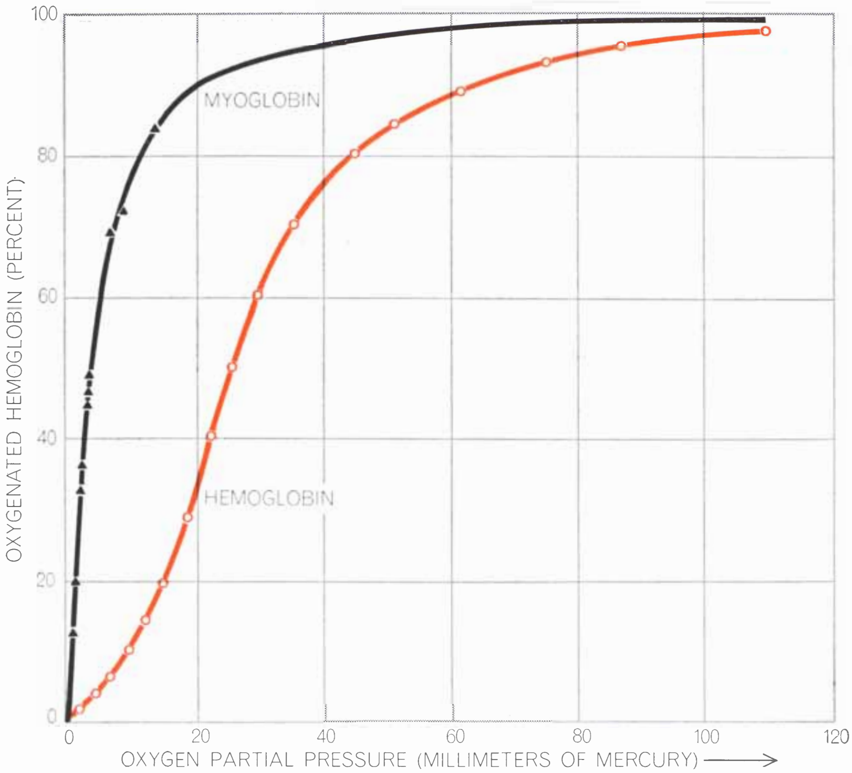
In brief, the various repressors in the cell are specialized receptors, each capable of recognizing a specific signal. And within its chromosomes a cell possesses instructions for synthesizing a wide variety of enzymes, each of which can be evoked simply by the presentation of the appropriate signal to the appropriate repressor.

The cell's selection of chromosomal records for transcription is so efficient as to seem almost "conscious." Actually, however, the responses of the cell are automatic, and like any other automatic mechanism they can be "tricked." It is as though a vending machine were made to work by a false coin: certain artificial compounds closely resembling lactose are excellent inducers of lactase but cannot be broken down by the enzyme. This means that the cell is tricked into spending energy to make an enzyme it cannot use. The signal works, but it is a false alarm. Trickery in the opposite direction is also possible. There is an analogue of tryptophan, called 5-methyl tryptophan, that acts as a repressive signal, causing the cell to stop its production of tryptophan. But 5-methyl tryptophan cannot be incorporated into protein in place of the genuine amino acid. Without that essential amino acid the cell stops growing and dies of starvation. Thus the false signal in effect acts as an antibiotic.

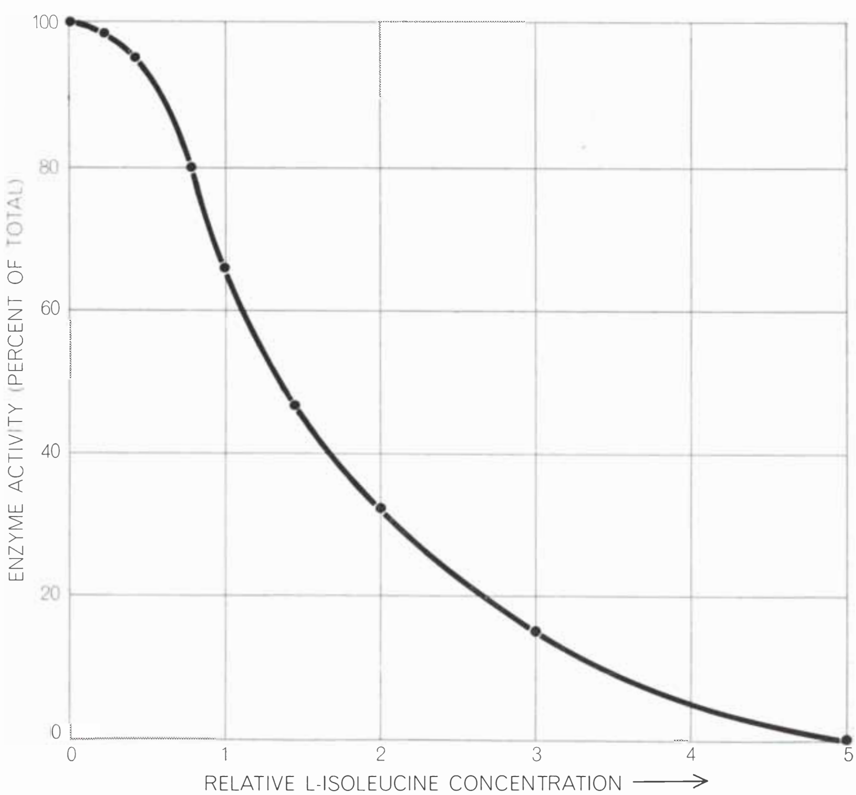
If chemical signals control the production of enzymes, may they not also control the more generalized activities of the cell, notably its self-replication? Jacob, Sydney Brenner and François Cuzin, working cooperatively at the Pasteur Institute and at the Laboratory of Molecular Biology at the University of Cambridge, recently discovered evidence of such a chemical control. They investigated the replication of the unique circular chromosome of *E. coli*. The synthesis of the deoxyribonucleic acid (DNA) of the chromosome, they found, is initiated by a signaling molecule that corresponds to the repressor of enzyme synthesis. The "initiator" has a positive effect rather than a repressive one. Like the repressor of enzyme synthesis, it is synthesized under the direction of a regulatory gene for replication. As the cell prepares for division, the initiator receives orders from the cell membrane and triggers the replication of its DNA by activating a genetic structure called the replicator (analogous to the "operator" of enzyme synthesis). Not much information has been gathered so far about the signal that prompts the initiator or about the



TWO NUCLEOTIDES, adenosine triphosphate (ATP) and cytidine triphosphate (CTP), are required by the cell in fixed proportions, so their production is regulated by interconnected feedback mechanisms operating on the first enzymes in the synthetic chains. In the case of CTP the enzyme is aspartate transcarbamylase (ATCase). It is inhibited by an excess of CTP (*1*), activated by an excess of ATP (*2*) and must also recognize and respond to the "cooperative" effects of aspartate, its substrate (*3*), which also plays a role in protein synthesis. Notice that ATP, CTP and aspartate have different shapes. How, then, can they all "fit" ATCase chemically?



HEMOGLOBIN, like an enzyme, is a large molecule that binds a small one (oxygen) at specific sites. The curves show the rate of oxygen-binding by hemoglobin (*color*) and myoglobin (*black*), a related oxygen-carrier in muscle. The myoglobin curve is a hyperbola but the hemoglobin curve is *S*-shaped. Hemoglobin binds best at higher oxygen concentrations (in the lungs); the binding of a few oxygen molecules favors the binding of more.



"COOPERATIVE EFFECT" occurs in regulatory enzymes as in hemoglobin. This curve shows the inhibition of L-threonine deaminase by L-isoleucine. The curve's *S* shape indicates that the effect of the regulatory signal is significant only above a threshold value.

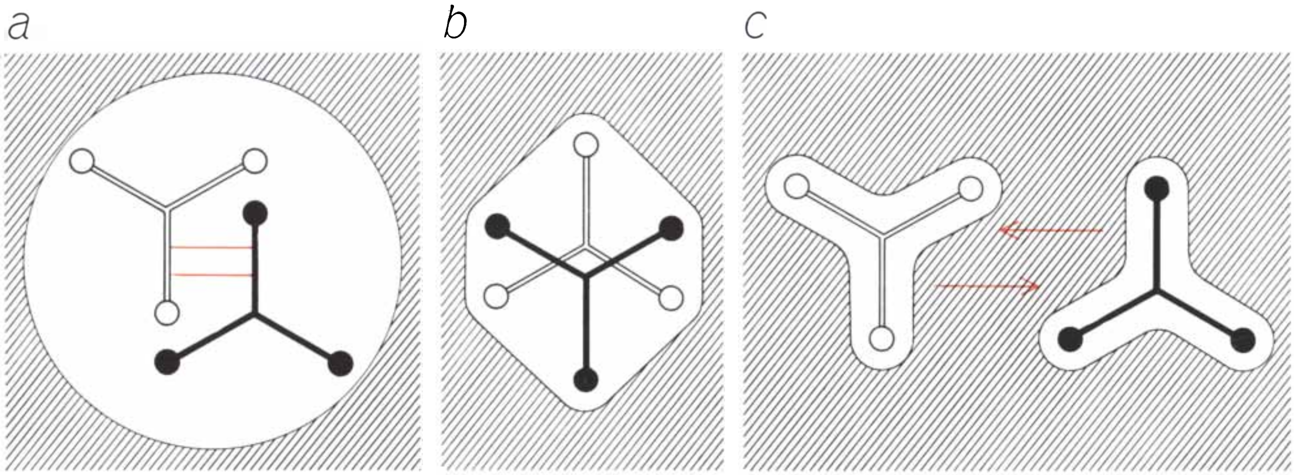
details of the machinery it sets in motion, but it seems clear that cell division has its own system of chemical control and that it can adjust itself to the composition of the growth medium.

We have been considering the control of the synthesis of enzymes; now let us turn to the control of their activity. As I have mentioned, Umbarger and his colleagues found that the presence of L-isoleucine would not only cause *E. coli* to stop synthesizing the enzymes needed for its production but also inhibit the activity of the first enzyme in the chain leading to the formation of the amino acid. The phenomenon of control of enzyme activity had already been noted earlier in the 1950's by Aaron Novick and Leo Szilard of the University of Chicago. They had shown that an excess of tryptophan in the *E. coli* cell halted the cell's production of tryptophan immediately, which means that the signal inhibited the activity of enzymes already present in the cell. Umbarger went on to investigate the direct effect of L-isoleucine on the enzymes that synthesize it; these had been extracted from the cell. He demonstrated that L-isoleucine inhibited the first enzyme in the chain (L-threonine deaminase), and only the first. This action was extremely specific; no other amino acid—not even D-isoleucine, the mirror image of L-isoleucine—had any effect on the enzyme's activity.

One must pause to remark on the extraordinary economy and efficiency of this control system. As soon as the supply of L-isoleucine reaches an adequate level, the cell stops making it at once. The signal acts simply by turning off the activity of the first enzyme; that is enough to stop the whole production line. Most remarkable of all, once this first enzyme has been synthesized the control costs the cell no expenditure of energy whatever; this is shown by the fact that the amino acid will act to inhibit the enzyme outside the cell without any energy being supplied. A factory with control relays that require no energy for their operation would be the ultimate in industrial efficiency!

The L-isoleucine control system of *E. coli* is only one example of this type of regulation in the living cell. It has now been demonstrated that similar circuits control the cell's production of the other amino acids, vitamins and other major substances, including the purine and pyrimidine bases that are the precursors of DNA.

In all these cases the control is nega-

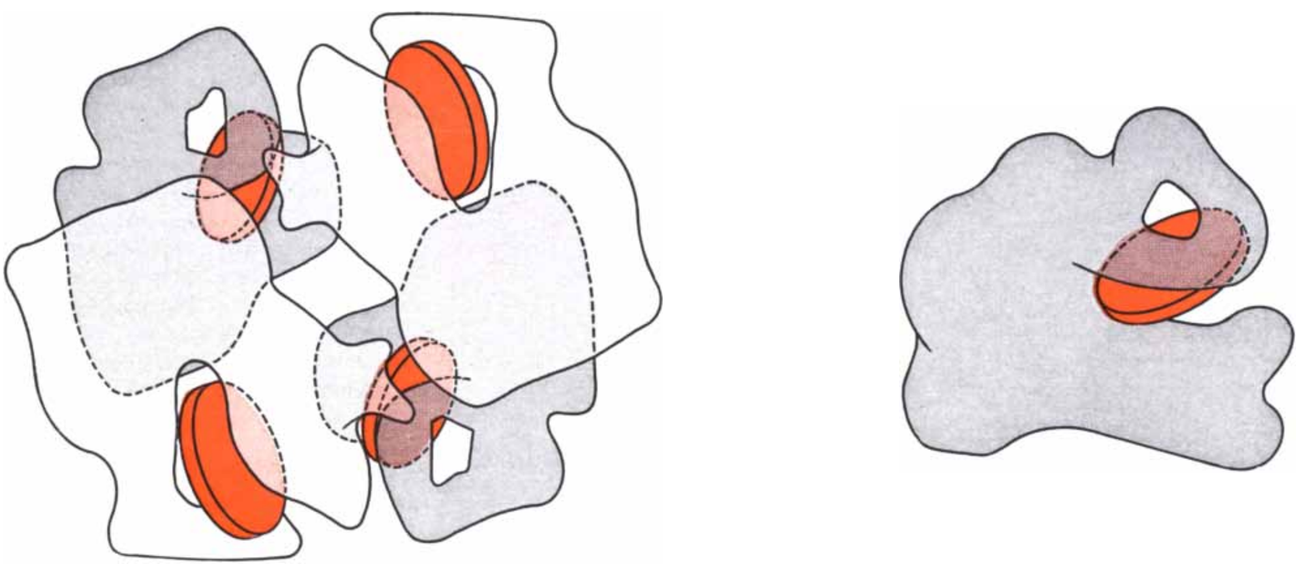


REGULATORY PROPERTY of an enzyme might be explained in three different ways. A regulatory signal (*open shape*) might combine with the substrate (*black shape*), participating directly in the chemical reaction it is controlling (*a*). But no such compounds have been found. A signal could simply get in the way of the substrate, excluding it from the enzyme's active site by "steric hindrance" (*b*). The different shapes of substrates and signals preclude this, and in any case steric hindrance could only account for enzyme inhibition, not activation. The only plausible hypothesis, confirmed by experiments with several enzymes, is that the signals and the substrate fit different sites on the enzyme and that the regulatory interactions of these sites are "allosteric," or indirect (*c*).

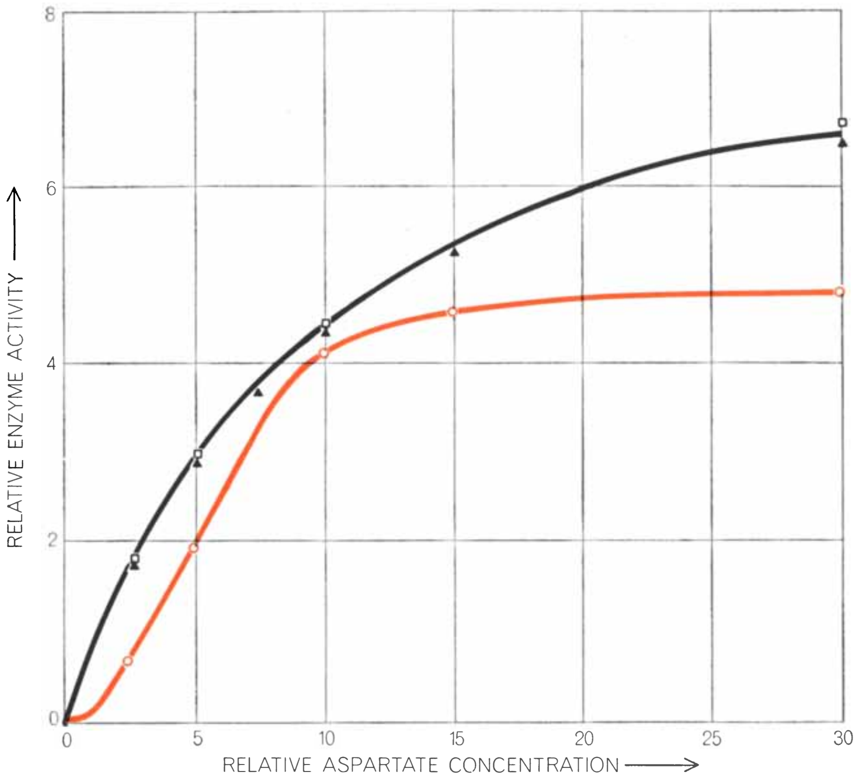
tive; that is, it involves the inhibition of enzymes. There are opposite situations, of course, in which the control system *activates* an enzyme when the circumstances call for it. An excellent example of such a positive control has to do with the cell's storage and use of energy.

Animal cells store reserve energy in the form of glycogen, or animal starch. Glycogen is synthesized from a precursor—glucose-6-phosphate—in three enzymatic steps. First glucose-6-phosphate is made into glucose-1-phosphate; then glucose-1-phosphate is made into uridine diphosphate D-glucose. Finally uridine diphosphate D-glucose is made into glycogen. When the cell has a good supply of energy, it produces considerable amounts of glucose-6-phosphate. This serves as a signal for stimulating the synthesis of glycogen. The signal works at the third step: the presence of a high level of glucose-6-phosphate strongly activates the enzyme that brings about the conversion of uridine diphosphate D-glucose into glycogen. On the other hand, when the supply of working energy in the cell falls to a low level, so that it must draw on the reserve stored in glycogen, it becomes necessary to activate an enzyme that splits the glycogen (the enzyme known as glycogen phosphorylase). One chemical signal known to be capable of activating this enzyme is adenosine monophosphate (AMP). AMP is a product of the splitting of adenosine triphosphate (ATP), the principal source of the cell's working energy, and an accumulation of AMP therefore indicates that the cell has used up its energy. The AMP signal activates the glycogen-splitting enzyme; the enzyme splits the glycogen molecule; the splitting releases energy, and the energy then is used to regenerate ATP.

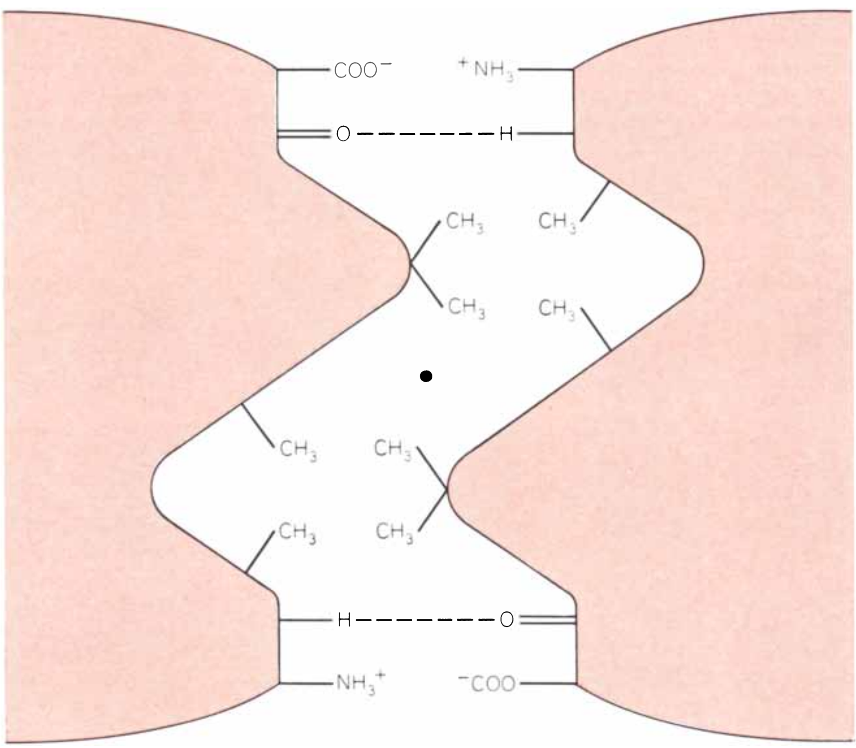
The cell thus possesses mechanisms for two types of control of enzyme activity: negative (inhibited enzymes) and positive (activated enzymes). There are



MOLECULE OF HEMOGLOBIN, shown (*left*) in very simplified form, has four heme groups (*color*), each of which is borne on a subunit, or chain, that is very similar to a myoglobin molecule (*right*). The heme groups of hemoglobin, each of which is a binding site for an oxygen molecule, are relatively far apart. Cooperative interactions among them must therefore be "allosteric."



DESENSITIZATION of an enzyme affects all its regulatory properties. The substrate saturation curve of natural ATCase (*color*) is S-shaped as a result of the cooperative effect. If the enzyme is denatured by heating, the cooperative effect is lost (*black curve*). So is the effect of feedback inhibition by CTP, as shown by the fact that the curve is the same whether the enzyme is assayed without CTP (*triangles*) or with CTP added (*squares*).



ALLOSTERIC PROTEINS are assumed by Monod, Jeffries Wyman and the author to be polymers, molecules composed of identical subunits, that have a definite axis of symmetry (*black dot*). A cross section through such a molecule (made up in this case of two subunits) shows how the symmetry results from the chemical bonds by which the units are associated.

situations in which both methods operate simultaneously. Consider, for example, the synthesis of a nucleic acid. It is assembled from purine and pyrimidine bases, combined in certain definite proportions. The purines and pyrimidines are synthesized on parallel production lines. For the sake of economy they should be produced roughly in the proportions in which they will be used.

This implies that the rate of production by each production line should feed back to control the output by the other. Such a system of mutual regulation must employ both negative and positive controls. Exactly this kind of system has been demonstrated in experiments with *E. coli* conducted by John C. Gerhart and Pardee at the University of California at Berkeley and at Princeton University. They showed that the output of the pyrimidine production line is controlled not only by its own end product (which inhibits the first enzyme in the synthetic sequence) but also by the end product of the purine production line, which counteracts the inhibition by the pyrimidine end product in vitro. Indeed, the purine end product can activate the pyrimidine production directly when no pyrimidine product is present! In short, the enzyme involved here is inhibited by one signal and activated by another.

Several enzymes involved in regulation have also been found to respond in this way to different signals. Moreover, this is not the only exceptional property of these enzymes. Let us now consider another property that will clarify the mechanism by which they are controlled.

A clue to this property seems to lie in the shape of the curve describing the rate at which the enzymes react with their substrates: the substances whose changes they catalyze. Ordinarily the rate of reaction of an enzyme increases as the concentration of substrate is increased. The increase is described by an experimental curve that fits a hyperbola. This kind of curve expresses the fact that the first step in the transformation of the substrate by the enzyme is the binding of the substrate to a specific attachment site on the enzyme.

When the concentration of substrate is increased, molecules of substrate tend to occupy more and more binding sites. Since the number of enzyme molecules is limited, at high concentrations of substrate nearly all the binding sites are occupied. At this point the rate of reaction levels off, hence the hyperbolic shape of the curve. The regulatory enzymes, surprisingly, do not exactly follow this pattern: their reaction rate increases with the concentration of substrate but often the curve is sigmoid (S-shaped) rather than hyperbolic.

When one reflects on the saturation curve of the regulatory enzymes, one notes that it is strikingly like the curve describing the saturation of the hemoglobin of the blood with oxygen. There too the reaction rate traces a sigmoid curve; this remarkable property is related to hemoglobin's physiological function of carrying oxygen from the lungs to other tissues. In the lungs, where the oxygen pressure is high, the hemoglobin is readily charged with the gas; in the tissues, where the oxygen pressure is low, the hemoglobin readily discharges its oxygen. Consider now, however, the myoglobin of muscle tissue. It takes on oxygen, but its oxygenation follows a hyperbolic curve like the classical one for enzymes. A comparative chart shows that when the pressure of oxygen is increased, the amount of oxygen bound by hemoglobin increases faster than the amount bound by myoglobin [*see top illustration on page 40*]. It looks as if the first oxygen molecules picked up by the hemoglobin favor the binding of others—as if there is cooperation among the oxygen molecules in binding themselves to the carrier. Oxygen thus plays the role of a regulatory signal for its own binding.

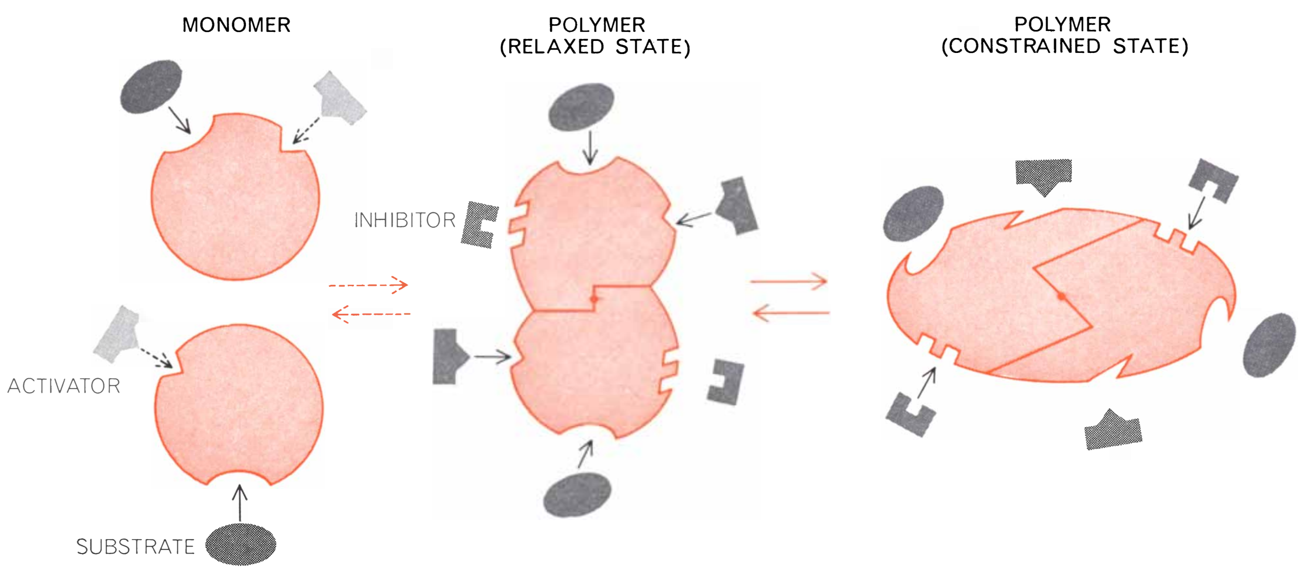
Similarly, cooperation may be the key to the sigmoid pattern of binding activity in many of the regulatory enzymes. An example of such an enzyme is threonine deaminase. Here again physiological function is evident. The substrate of threonine deaminase is the amino acid threonine. If the amount of this amino acid falls to a very low level in the cell, the cell cannot synthesize proteins. In the absence of threonine, it would be a waste of energy to make isoleucine, the end product of the chain of which threonine deaminase is the first step; hence the economy-geared control system of the cell calls off the production of the second amino acid. In other words, threonine deaminase will not be active and isoleucine will not be produced unless at least threshold concentrations of threonine are present in the cell. In this situation threonine plays the role of regulatory signal for the reaction of which it is the specific substrate; it is an activator of its own transformation.

The most remarkable part of the story is that such cooperative effects are not restricted to the binding of substrate but also operate in the binding of more familiar regulatory signals: specific inhibitors or activators. Regulatory enzymes appear to be built in such a way that they not only recognize the configuration of specific substrates as signals but also gauge their response to whether or not the substrates and regulatory signals are present in certain threshold concentrations. (This is strongly reminiscent, of course, of electric relays—and, one may add, of nerve cells—which react only if the signal has a certain threshold strength.) The regulatory enzymes are thus capable of integrating several signals—both positive and negative—that modulate their activity.

We come now to the question: How do the regulatory relays work? The signals (either activators or inhibitors) are usually small molecules, and the receptor is a regulatory enzyme. In chemical terms, how does the enzyme translate and integrate the signals it receives? The answer to this question applies not only to regulatory enzymes but also to any other molecule that mediates a regulatory interaction. Since little is known about many of these molecules, the model I shall now describe is based on the experimental results obtained from regulatory enzymes. It seems legitimate, however, to extend the model to any category of regulatory molecule.

The question presents a biochemist with a difficult paradox. A molecule can "recognize" a message only in terms of geometry, that is, the shape or configuration of the molecule bearing the message. In this case the message is supposed to cause the enzyme to carry out (or refrain from carrying out) a certain reaction: conversion of a specific substrate into a specific product. Yet the molecule bearing the message often has no structural likeness to either the substrate or the product! How, then, can it promote or interfere with the enzyme's performance of its specific catalytic action on this substrate?

Considering several possible explana-



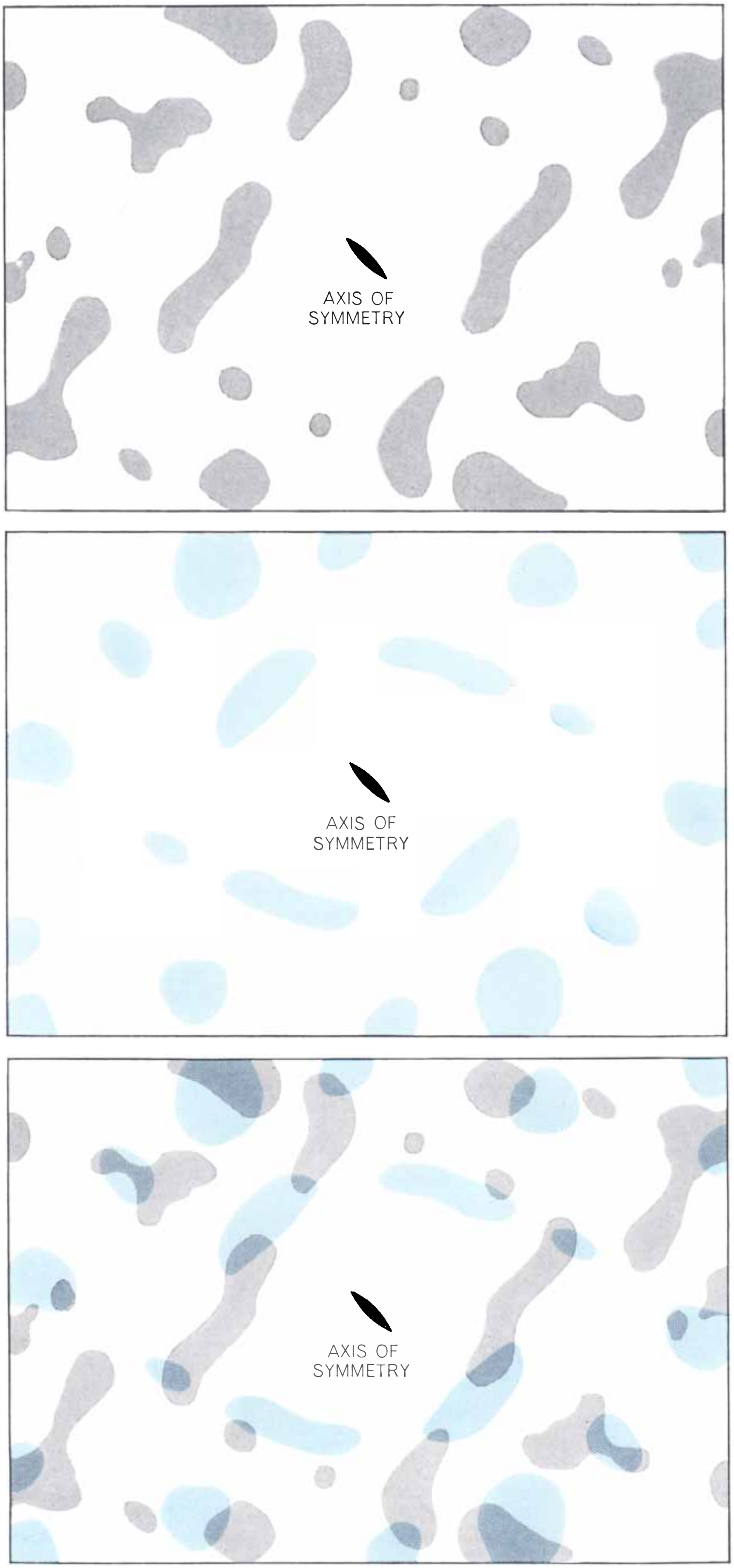
REGULATORY CHANGES in an allosteric molecule are conceived of as arising from its shifting back and forth between two states. The polymeric molecule is made up of several monomers (two in this case), as shown at left. The polymer can exist in a "relaxed" state (*middle*) or a "constrained" state (*right*). In one condition it binds substrate and activators; in the other state it binds inhibitors. The binding of a signal tilts the balance toward one or the other state but the molecule's symmetry is preserved.

tions, Monod, Jacob and I have concluded that the only plausible one is that the signal and the substrate fit into separate binding sites on the enzyme and that the signal takes effect by an interaction between these sites [*see top illustration on page 41*]. There is strong experimental evidence in favor of this model. One of the most convincing lines of evidence is the recent discovery by Gerhart that the regulatory enzyme aspartate transcarbamylase has a binding site for its substrate on one subunit of the molecule and a site for an inhibitor of its activity on another subunit. When the subunits are split apart, one retains the ability to recognize the substrate, the other the ability to recognize the inhibitor.

We must now inquire into the nature of the interaction of these two categories of sites on the enzyme. How does the binding of a molecule at one site affect the binding of another molecule at the other site? The best clue to an understanding of the mechanism of the interaction seems to lie in a property of regulatory enzymes that I have already mentioned: the sigmoid curve describing their binding of substrate or of signal molecules, which indicates a cooperative effect among those molecules. Again it is instructive to consider the analogy of the binding of oxygen molecules by hemoglobin.

The hemoglobin molecule has four hemes that are well separated from one another; each is a binding site for an oxygen molecule. In view of the separation between the sites, their cooperation in binding oxygen must be "allosteric," or indirect. Myoglobin, which has only one binding site, binds oxygen hyperbolically (that is, without any control); hemoglobin, with its four sites, binds oxygen in a sigmoid pattern. It seems, therefore, that the key to hemoglobin's cooperative, controlled binding of oxygen lies in the molecule's four-part structure.

Now consider a regulatory enzyme. The binding of any particular molecule



EXPERIMENTAL DATA supporting the allosteric model come from X-ray diffraction maps of hemoglobin made by M. F. Perutz and his colleagues at the University of Cambridge. The contour lines based on electron densities suggest the shapes of the subunit chains of oxygenated hemoglobin (*top*), reduced hemoglobin (*middle*) and the two superposed (*bottom*). A conformational change of the kind proposed in the model on the preceding page is evident, as is preservation of the molecule's axis of symmetry.

(substrate, inhibitor or activator) is sigmoid and therefore a cooperative affair; this implies that there is a set of reception sites for each specific molecule. There also appears to be interaction among the binding sites for different molecules, such as substrate and activator or substrate and inhibitor. Surprisingly the experimental evidence suggests that both types of allosteric interaction—that among the sites binding a particular molecule and that among the sites binding different molecules—may depend on one and the same mechanism, embodied in the structure of the enzyme molecule.

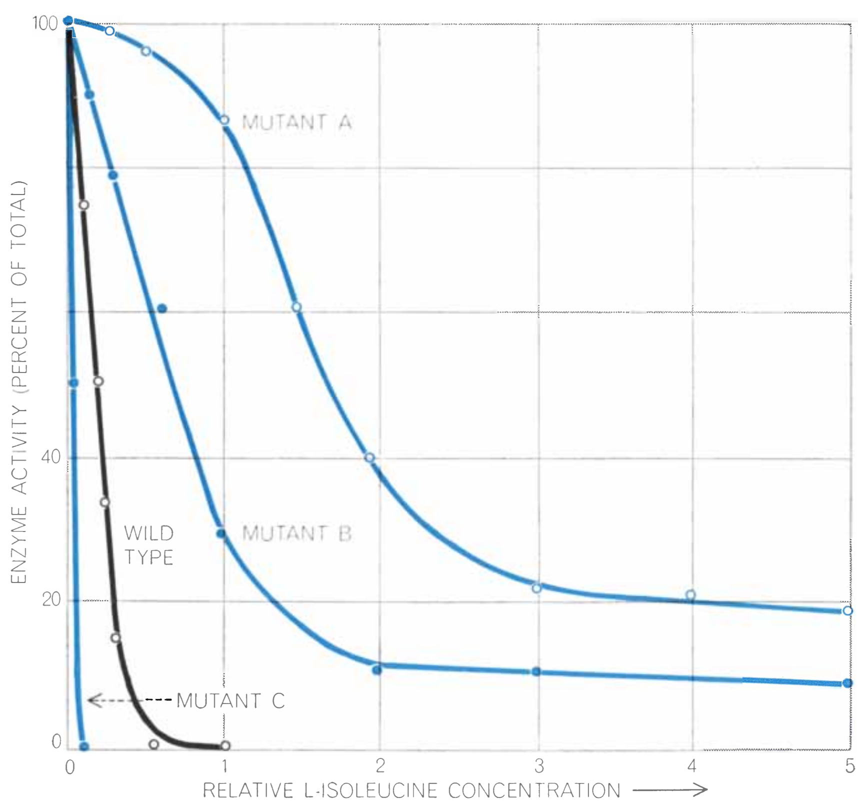
The most striking evidence comes from experiments in the alteration of the structure of regulatory enzyme molecules. Gerhart and Pardee at Berkeley and Princeton and I at the Pasteur Institute, working independently, have found that by changing the molecular structure of aspartate transcarbamylase or L-threonine deaminase (by means of heat, bacterial mutation or certain other procedures) it is possible to "desensitize" these regulatory enzymes so that they are no longer affected by a feedback inhibitor. They are still capable, however, of reacting with their respective substrates. The interesting point is that a change in the enzyme's structure eliminates, along with the negative interaction of the feedback inhibitor and the substrate, all the cooperative interactions in the enzyme molecule. This applies particularly to the binding of the substrate, which changes from a sigmoid to a hyperbolic pattern.

What, then, is the crucial structural feature that accounts for the allosteric interactions within the enzyme molecule? Again hemoglobin offers a clue.

We have noted that the hemoglobin molecule is a four-part structure. It comprises four heme units, each of which is attached to a distinct chain of amino acid units. This molecule is thus made up of four subunits, each of which is so similar to a myoglobin molecule that hemoglobin can be considered essentially a combination of four myoglobin molecules. Hemoglobin displays cooperative interaction, whereas myoglobin does not; hence this property evidently is associated with its four-part structure. Now, experiments show that the binding of oxygen by hemoglobin is connected in some way with an adjustment in the bonding between the subunits making up the molecule [see "The Hemoglobin Molecule," by M. F. Perutz; SCIENTIFIC AMERICAN, November, 1964]. The same turns out to be true of many of the regulatory enzymes; their binding of smaller molecules also depends on the adjustment of the bonds holding together their subunits.

On the strength of the experimental findings, Monod, Jeffries Wyman and I have proposed a model picturing the working of the regulatory enzyme system [*see illustration on page 43*]. It suggests that the enzyme molecule consists of a set of identical subunits, each subunit containing just one specific site for each of the molecules it may bind to itself, either substrate molecules or regulatory signals. Now, if a molecule is made up of a definite and limited number of subunits, the implication is that it has an axis of symmetry. Let us say that the enzyme molecule can switch back and forth between two states, and that in each state its symmetry is preserved. The two symmetrical states differ in the energy of bonding between the subunits: in the more relaxed state the enzyme molecule will preferentially bind activator and substrate; in the more constrained state it will bind inhibitor. Whichever compound it binds (substrate, inhibitor or activator) will tip the balance so that it then favors the binding of that category of small molecule. A change in the relative concentrations of substrate and signals may, depending on their molecular structure, tip the balance one way or the other. Thus the model indicates how the enzyme molecule's binding sites may interact, either cooperatively or antagonistically. It suggests that the enzyme may integrate different messages simply by adopting a characteristic state of spontaneous equilibrium between two states.

The major conclusion from the study of the regulatory enzymes is that their powers of control and regulation depend entirely on the form of their molecular structure. Built into that structure, as into a computer, is the capacity to recognize and integrate various signals. The enzyme molecule responds to the signals automatically with structural modifications that will determine the rate of production of the product in question. How did these biological "computers" come into being? Obviously they must owe their remarkable properties to nature's game of genetic mutation and selection, which in eons of time has refined their construction to a peak of exquisite efficiency.



MUTATIONS in the structural gene for L-threonine deaminase in *E. coli* affect the regulatory properties of the enzyme. Mutant enzymes respond differently to feedback inhibition.

ATTITUDE AND PUPIL SIZE

Dilation and constriction of the pupils reflect not only changes in light intensity but also ongoing mental activity. The response is a measure of interest, emotion, thought processes and attitudes

by Eckhard H. Hess

One night about five years ago I was lying in bed leafing through a book of strikingly beautiful animal photographs. My wife happened to glance over at me and remarked that the light must be bad—my pupils were unusually large. It seemed to me that there was plenty of light coming from the bedside lamp and I said so, but she insisted that my pupils were dilated. As a psychologist who is interested in visual perception, I was puzzled by this little episode. Later, as I was trying to go to sleep, I recalled that someone had once reported a correlation between a person's pupil size and his emotional response to certain aspects of his environment. In this case it was difficult to see an emotional component. It seemed more a matter of intellectual interest, and no increase in pupil size had been reported for that.

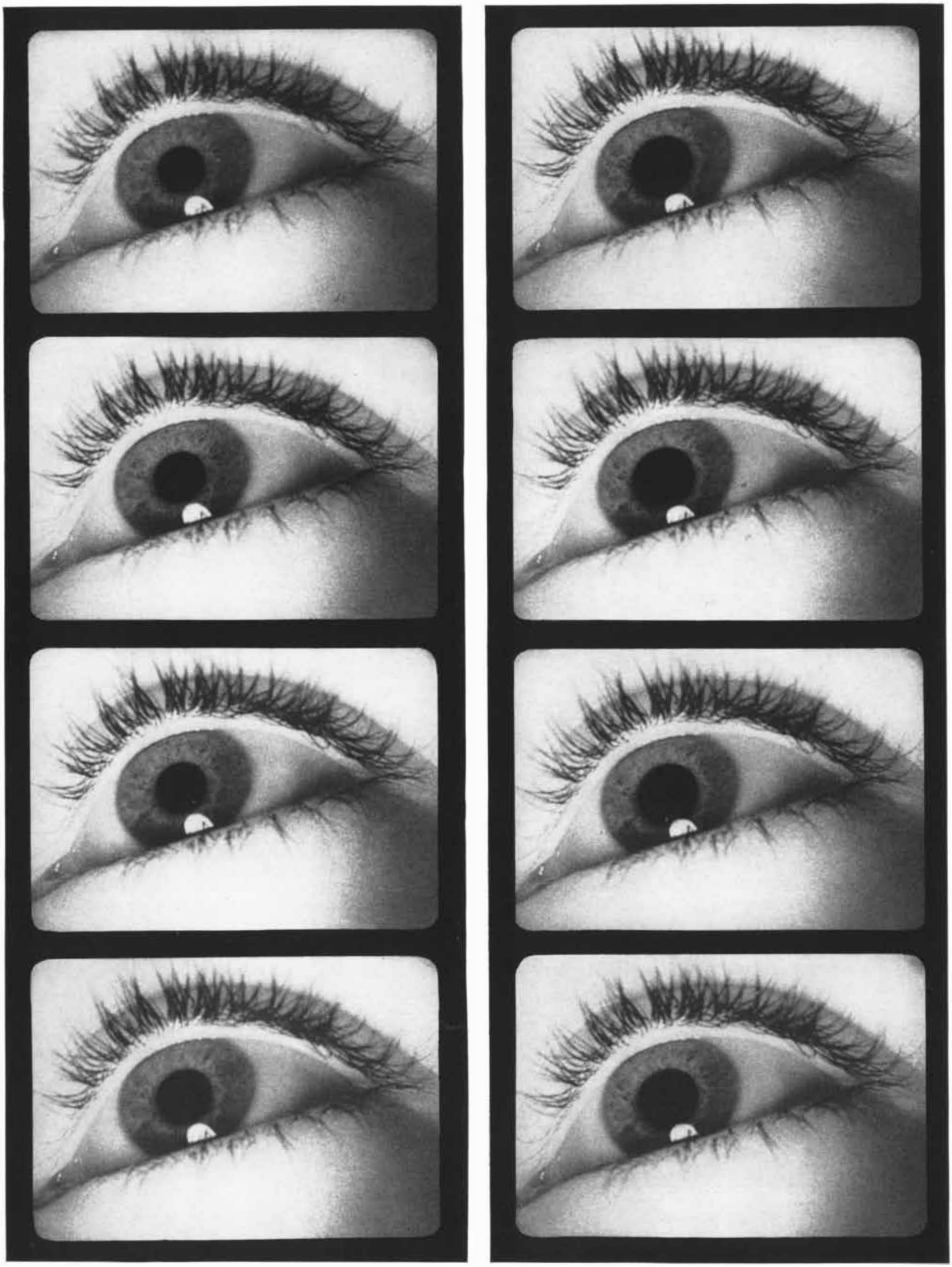
The next morning I went to my laboratory at the University of Chicago. As soon as I got there I collected a number of pictures—all landscapes except for one seminude "pinup." When my assistant, James M. Polt, came in, I made him the subject of a quick experiment. I shuffled the pictures and, holding them above my eyes where I could not see them, showed them to Polt one at a time and watched his eyes as he looked at them. When I displayed the seventh picture, I noted a distinct increase in the size of his pupils; I checked the picture, and of course it was the pinup he had been looking at. Polt and I then embarked on an investigation of the relation between pupil size and mental activity.

The idea that the eyes are clues to emotions—"windows of the soul," as the French poet Guillaume de Salluste wrote—is almost commonplace in literature and everyday language. We say "His eyes were like saucers" or "His eyes were pinpoints of hate"; we use such terms as "beady-eyed" or "bug-eyed" or "hard-eyed." In his *Expressions of Emotion in Man and Animals* Charles Darwin referred to the widening and narrowing of the eyes, accomplished by movements of the eyelids and eyebrows, as signs of human emotion; he apparently assumed that the pupil dilated and contracted only as a physiological mechanism responsive to changes in light intensity.

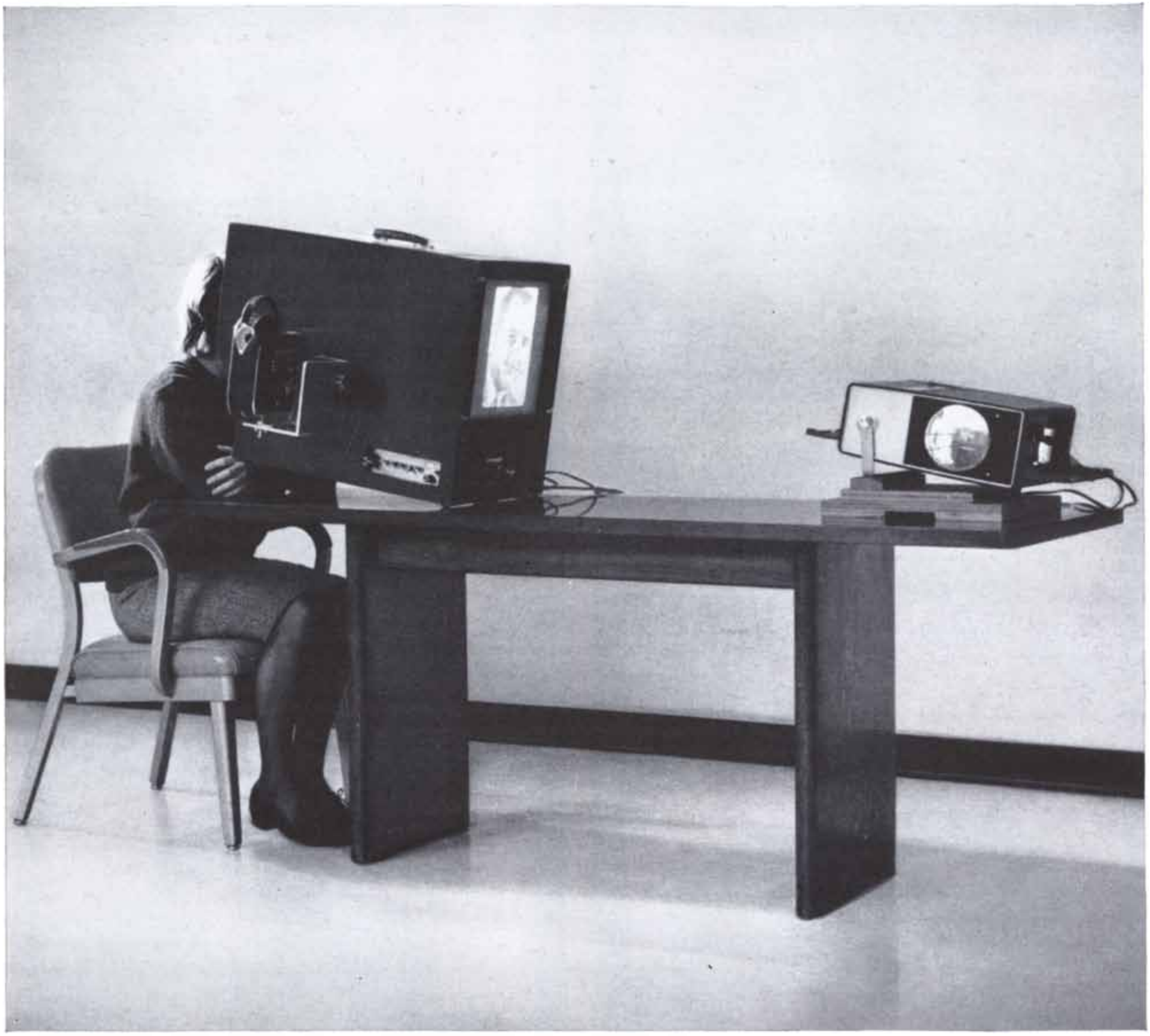
This light reflex is controlled by one of the two divisions of the autonomic nervous system: the parasympathetic system. Later investigators noted that pupil size is also governed by the other division of the autonomic system—the sympathetic system—in response to strong emotional states and that it can vary with the progress of mental activity. On a less sophisticated level some people to whom it is important to know what someone else is thinking appear to have been aware of the pupil-size phenomenon for a long time. It is said that magicians doing card tricks can identify the card a person is thinking about by watching his pupils enlarge when the card is turned up, and that Chinese jade dealers watch a buyer's pupils to know when he is impressed by a specimen and is likely to pay a high price. Polt and I have been able to study the pupil response in detail and to show what a remarkably sensitive indicator of certain mental activities it can be. We believe it can provide quantitative data on the effects of visual and other sensory stimulation, on cerebral processes and even on changes in fairly complex attitudes.

Most of our early experiments related pupil size to the interest value and "emotionality" of visual stimuli. Our techniques for these studies are quite simple. The subject peers into a box, looking at a screen on which we project the stimulus picture. A mirror reflects the image of his eye into a motion-picture camera. First we show a control slide that is carefully matched in overall brightness to the stimulus slide that will follow it; this adapts the subject's eyes to the light intensity of the stimulus slide. At various points on the control slide are numbers that direct the subject's gaze to the center of the field. Meanwhile the camera, operating at the rate of two frames per second, records the size of his pupil. After 10 seconds the control slide is switched off and the stimulus slide is projected for 10 seconds; as the subject looks at it the camera continues to make two pictures of his eye per second. The sequence of control and stimulus is repeated about 10 or 12 times a sitting. To score the response to a stimulus we compare the average size of the pupil as photographed during the showing of the control slide with its average size during the stimulus period. Usually we simply project the negative image of the pupil, a bright spot of light, on a screen and measure the diameter with a ruler; alternatively we record the changes in size electronically by measuring the area of the pupil spot with a photocell.

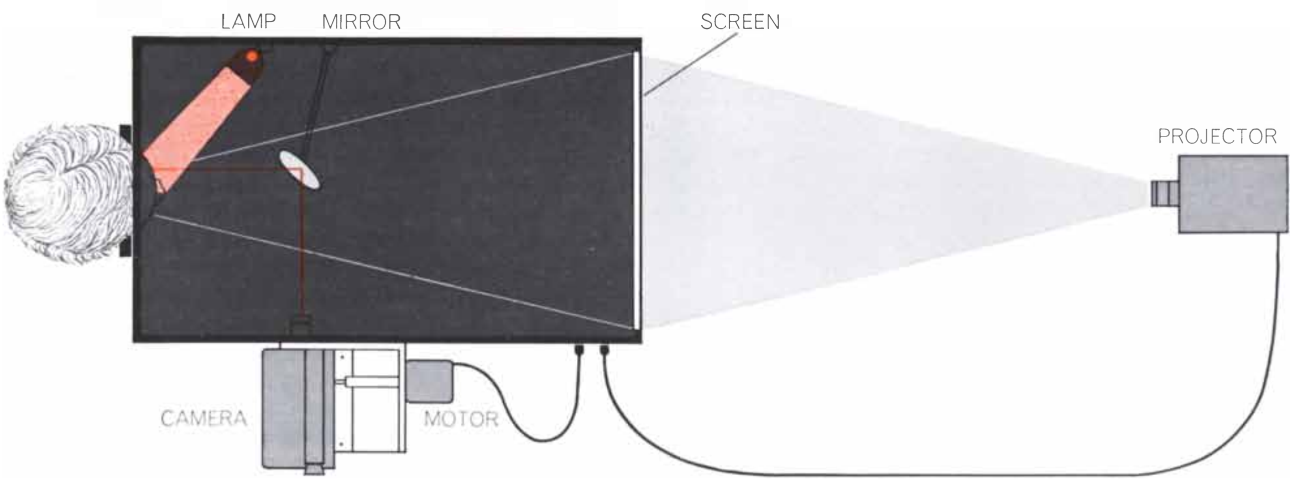
In our first experiment, before we were able to control accurately for brightness, we tested four men and two women, reasoning that a significant difference in the reactions of subjects of different sex to the same picture would be evidence of a pupil response to something other than light intensity. The results confirmed our expectations: the men's pupils dilated more at the sight of a female pinup than the women's



PUPIL SIZE varies with the interest value of a visual stimulus. In the author's laboratory a subject's eye is filmed as he looks at slides flashed on a screen. These consecutive frames (*top to bottom at left and top to bottom at right*) show the eye of a male subject during the first four seconds after a photograph of a woman's face appeared. His pupil increased in diameter 30 percent.



SUBJECT in pupil-response studies peers into a box, looking at a rear-projection screen on which slides are flashed from the projector at right. A motor-driven camera mounted on the box makes a continuous record of pupil size at the rate of two frames a second.



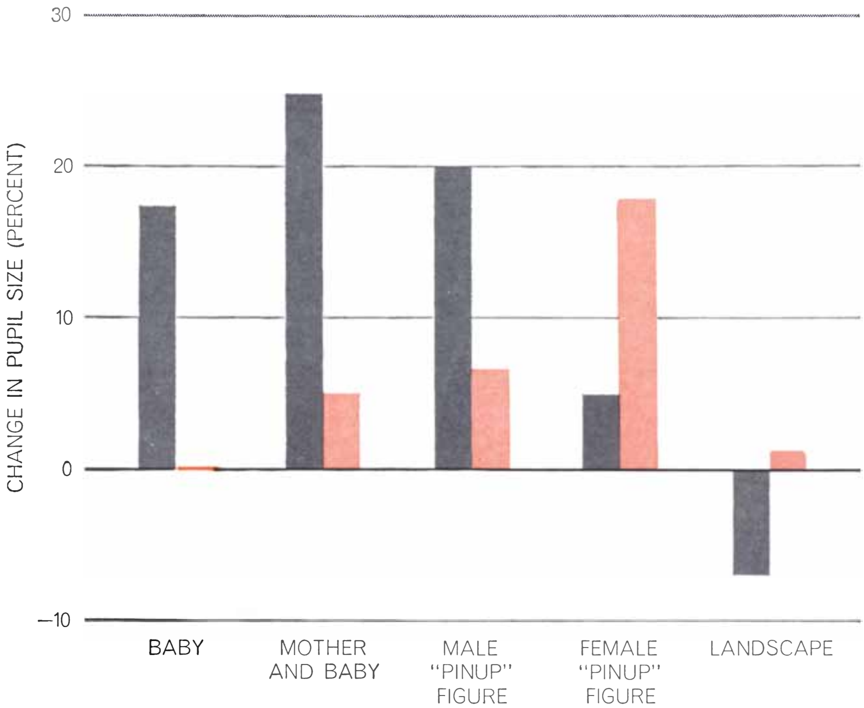
PUPIL-RESPONSE APPARATUS is simple. The lamp and the camera film work in the infrared. A timer advances the projector every 10 seconds, flashing a control slide and a stimulus slide alternately. The mirror is below eye level so that view of screen is clear.

did; the women showed a greater response than the men did to a picture of a baby or of a mother and baby and to a male pinup [*see illustration at right*]. We interpreted dilation in these cases as an indication of interest.

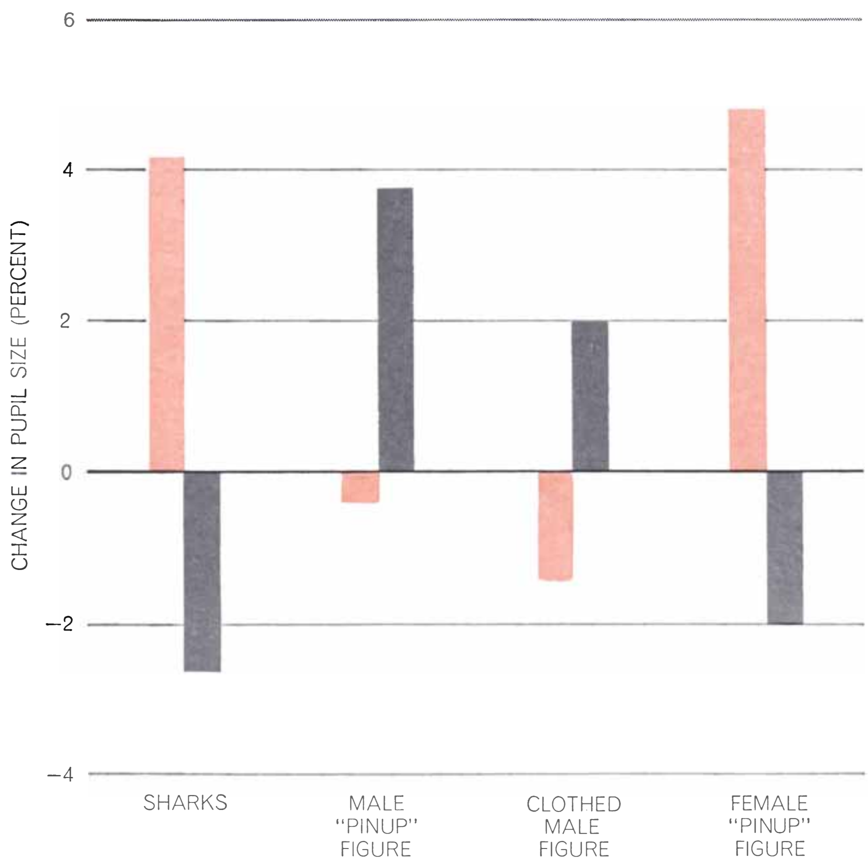
We then undertook another demonstration designed to eliminate the role of brightness. In this experiment we did not show a control slide; only the general room lighting illuminated the rear-projection screen of the apparatus during the control period. When the stimulus slide came on, every part of the screen was therefore at least somewhat brighter than it had been during the control period. If the eye responded only to changes in light intensity, then the response by all subjects to any stimulus ought to be negative; that is, the pupil should constrict slightly every time. This was not the case; we got positive responses in those subjects and for just those stimuli that would have been expected, on the basis of the results of the first study, to produce positive responses. We also got constriction, but only for stimuli that the person involved might be expected to find distasteful or unappealing.

These negative responses, exemplified by the reaction of most of our female subjects to pictures of sharks, were not isolated phenomena; constriction is as characteristic in the case of certain aversive stimuli as dilation is in the case of interesting or pleasant pictures. We observed a strong negative response, for example, when subjects were shown a picture of a cross-eyed or crippled child; as those being tested said, they simply did not like to look at such pictures. One woman went so far as to close her eyes when one of the pictures was on the screen, giving what might be considered the ultimate in negative responses. The negative response also turned up in a number of subjects presented with examples of modern paintings, particularly abstract ones. (We were interested to note that some people who insisted that they liked modern art showed strong negative responses to almost all the modern paintings we showed them.) The results are consistent with a finding by the Soviet psychologist A. R. Shachnowich that a person's pupils may constrict when he looks at unfamiliar geometric patterns.

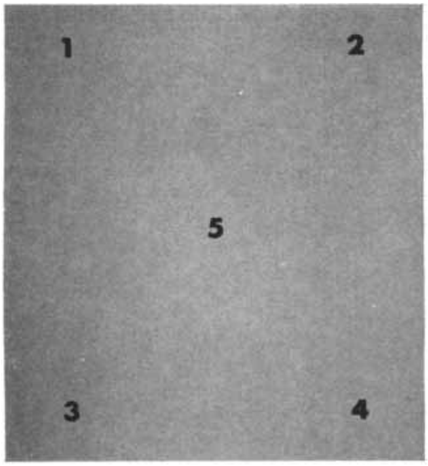
We have come on one special category of stimuli, examples of which are pictures of dead soldiers on a battlefield, piles of corpses in a concentration camp and the body of a murdered gang-



DIFFERENT RESPONSES to the same picture by female subjects (*gray bars*) and male (*colored bars*) established that the pupil response was independent of light intensity. The bars show changes in average area of pupils from the control period to the stimulus period.



ROLE OF BRIGHTNESS was also eliminated in an experiment in which the screen was unlighted before the stimulus appeared. Whereas responses to light alone would therefore have resulted in constriction, some pictures caused dilation in men (*colored bars*) and women (*gray*). In this experiment pupil diameter was tabulated rather than area.



CONTROL SLIDE provides calibration for experiments involving direction of gaze (*opposite page*). The subject looks at the five numbers in sequence and the camera records the resulting movements of his pupil.

ster. One might expect these to be "negative," and indeed they do produce extreme pupil constriction in some subjects, but they elicit a very different pattern of responses in others. On initial exposure the subject often responds with a large increase, rather than a decrease, in pupil size. Then, with repeated presentations, there is a shift to a negative response; the shift is usually accomplished after three to five exposures, and the time interval between those exposures seems to make little difference. Our impression was that these were negative stimuli with an additional "shock" content that prompted a strong emotional reaction. To check this hypothesis we attached electrodes to the hands of some of our volunteers and recorded their galvanic skin response, a measure of the electrical resistance of the skin that has been correlated with emotional level and is a component of most so-called lie-detector tests. As we had anticipated, stimuli we had classified as "shocking" got a high galvanic skin response along with the initial high pupil response in most subjects. After repeated presentations the skin response decreased rapidly as the pupil response shifted from dilation to constriction.

Although we have dealt primarily with positive stimuli, the evidence suggests that at least with respect to visual material there is a continuum of responses that ranges from extreme dilation for interesting or pleasing stimuli to extreme constriction for material that is unpleasant or distasteful to the viewer. In the presence of uninteresting or boring pictures we find only slight random variations in pupil size.

One of the most interesting things about the changes in pupil size is that they are extremely sensitive, sometimes revealing different responses to stimuli that at the verbal level seem to the person being tested quite similar. We once demonstrated this effect with a pair of stimulus photographs that in themselves provided an interesting illustration of the relation between pupil size and personality. In a series of pictures shown to a group of 20 men we included two photographs of an attractive young woman. These two slides were identical except for the fact that one had been retouched to make the woman's pupils extra large and the other to make them very small. The average response to the picture with the large pupils was more than twice as strong as the response to the one with small pupils; nevertheless, when the men were questioned after the experimental session, most of them reported that the two pictures were identical. Some did say that one was "more feminine" or "prettier" or "softer." None noticed that one had larger pupils than the other. In fact, they had to be shown the difference. As long ago as the Middle Ages women dilated their pupils with the drug belladonna (which means "beautiful woman" in Italian). Clearly large pupils are attractive to men, but the response to them—at least in our subjects—is apparently at a nonverbal level. One might hazard a guess that what is appealing about large pupils in a woman is that they imply extraordinary interest in the man she is with!

Pupillary activity can serve as a measure of motivation. We have investigated the effect of hunger, which is a standard approach in psychological studies of motivation. It occurred to us that a person's physiological state might be a factor in the pupil response when we analyzed the results of a study in which several of the stimulus slides were pictures of food—rather attractive pictures to which we had expected the subjects to respond positively. The general response was positive, but about half of the people tested had much stronger responses than the others. After puzzling over this for a while we checked our logbook and found that about 90 percent of the subjects who had evinced strong responses had been tested in the late morning or late afternoon—when, it seemed obvious, they should have been hungrier than the people tested soon after breakfast or lunch.

To be sure, not everyone is equally hungry a given number of hours after eating, but when we tested two groups controlled for length of time without food, our results were unequivocal: the pupil responses of 10 subjects who were "deprived" for four or five hours were more than two and a half times larger than those of 10 subjects who had eaten a meal within an hour before being tested. The mean responses of the two groups were 11.3 percent and 4.4 percent respectively.

Interestingly enough the pupils respond not only to visual stimuli but also to stimuli affecting other senses. So far our most systematic research on nonvisual stimuli has dealt with the sense of taste. The subject places his head in a modified apparatus that leaves his mouth free; he holds a flexible straw to which the experimenter can raise a cup of the liquid to be tasted. During the test the taster keeps his eyes on an *X* projected on the screen, and the camera records any changes in pupil size.

Our first study involved a variety of presumably pleasant-tasting liquids—carbonated drinks, chocolate drinks and milk—and some unpleasant-tasting ones, including concentrated lemon juice and a solution of quinine. We were surprised to find that both the pleasant and the unpleasant liquids brought an increase in pupil size compared with a "control" of water. Then we decided to test a series of similar liquids, all presumably on the positive side of the "pleasant-unpleasant" continuum, to see if, as in the case of visual material, some of the stimuli would elicit greater responses than others. We selected five "orange" beverages and had each subject alternate sips of water with sips of a beverage. One of the five orange beverages caused a significantly larger average increase in pupil size than the others did; the same drink also won on the basis of verbal preferences expressed by the subjects after they had been through the pupil-size test. Although we still have a good deal of work to do on taste, particularly with regard to the response to unpleasant stimuli, we are encouraged by the results so far. The essential sensitivity of the pupil response suggests that it can reveal preferences in some cases in which the actual taste differences are so slight that the subject cannot even articulate them—a possibility with interesting implications for market research.

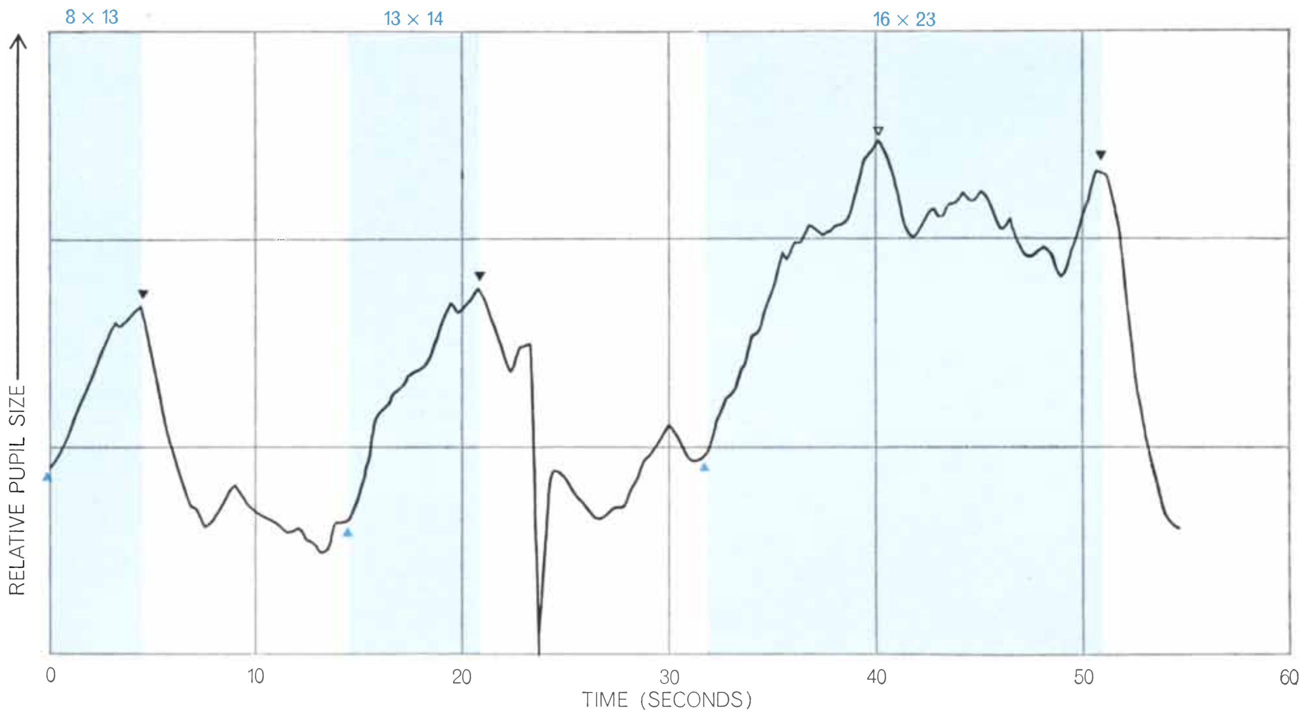
We have also had our volunteers listen to taped excerpts of music while

DIRECTIONAL ANALYSIS reveals where a subject was looking when each frame of film was made as well as how large his pupil was. Superposed on the upper reproduction of Leon Kroll's "Morning on the Cape" are symbols showing the sequence of fixations by a female subject looking at the painting; a man's responses are shown below. The light-color symbols indicate a pupil size about the same as during the preceding control period; open symbols denote smaller responses and dark-color symbols larger responses. The experimenters determine the direction of gaze by shining light through the film negative; the beam that passes through the image of the pupil is projected on a photograph of the stimulus (in this case the painting) and its position is recorded.

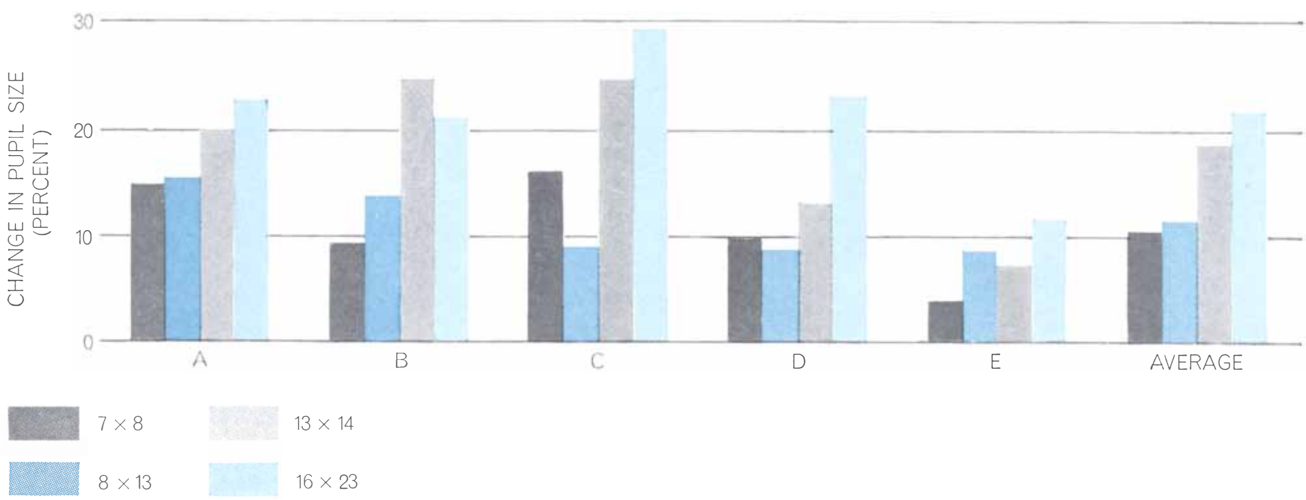
the camera monitors their pupil size. We find different responses to different compositions, apparently depending on individual preference. As in the case of the taste stimuli, however, the response to music seems always to be in a positive direction: the pupil becomes larger when music of any kind is being played. We have begun to test for the effect of taped verbal statements and individual words, which also seem to elicit different pupil responses. Research in these areas, together with some preliminary work concerning the sense of smell, supports the hypothesis that the pupil is closely associated not only with visual centers in the brain but also with other brain centers. In general it strongly suggests that pupillary changes reflect ongoing activity in the brain.

It is not surprising that the response of the pupil should be intimately associated with mental activity. Embryologically and anatomically the eye is an extension of the brain; it is almost as though a portion of the brain were in plain sight for the psychologist to peer at. Once it is, so to speak, "calibrated" the pupil response should make it possible to observe ongoing mental behavior directly and without requiring the investigator to attach to his subject electrodes or other equipment that may affect the very behavior he seeks to observe.

More than 50 years ago German psychologists noted that mental activity (solving arithmetical problems, for ex-



CHANGES IN PUPIL SIZE are traced in a subject doing the three mental-arithmetic problems shown at the top. Beginning when the problem is posed (*colored triangles*), the pupil dilates until the answer is given (*solid black triangles*). This subject appears to have reached a solution of the third problem (*open triangle*) and then to have reconsidered, checking his answer before giving it.

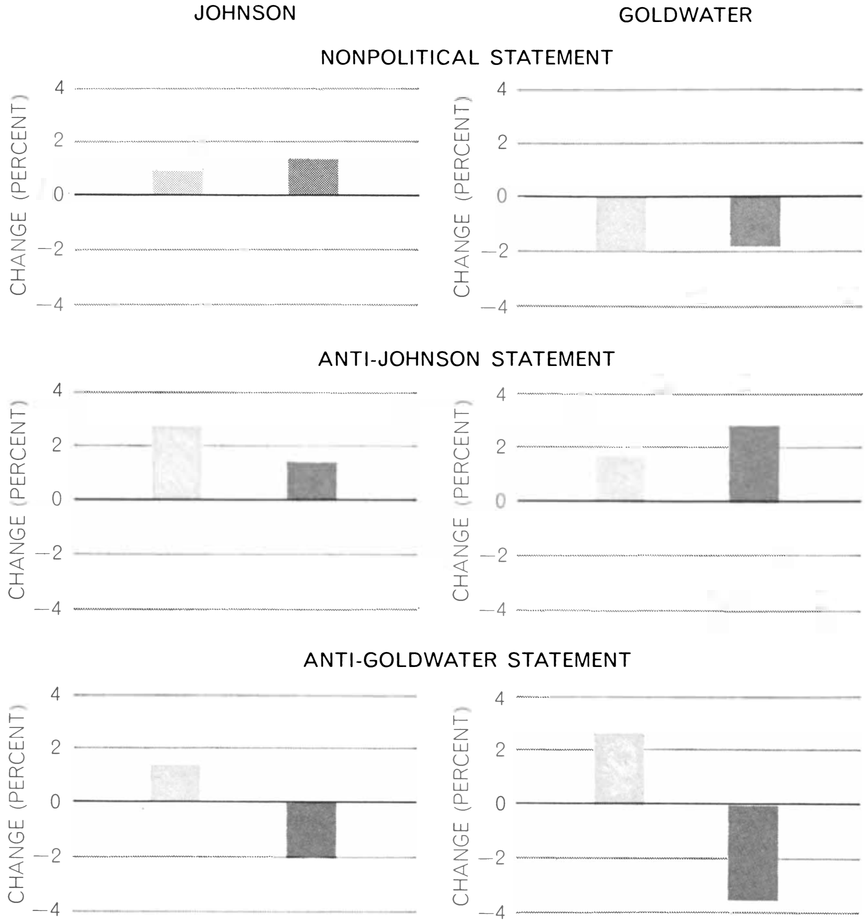


INDIVIDUAL DIFFERENCES in pupil response while solving multiplication problems reflect the fact that two of the five subjects, *D* and *E*, could do mental arithmetic with less effort than the others. The change in pupil size was computed by comparing the average size in the five frames before the problem was posed with the average in the five frames just before the answer was given.

ample) caused a gross increase in pupil size. We decided this would be a good area for detailed study in an effort to see how precise and differentiated an indicator the response could be. We present mental-arithmetic problems of varying difficulty to volunteers and then obtain a continuous trace of their pupil response by measuring the filmed images of the pupil with a photocell [*see upper illustration on opposite page*]. As soon as the problem is presented the size of the pupil begins to increase. It reaches a maximum as the subject arrives at his solution and then immediately starts to decrease, returning to its base level as soon as the answer is verbalized. If the subject is told to solve the problem but not give the answer, there is some decrease at the instant of solution but the pupil remains abnormally large; then, when the experimenter asks for the solution, the pupil returns to its base level as the subject verbalizes the answer.

In one study we tested five people, two who seemed to be able to do mental arithmetic easily and three for whom even simple multiplication required a lot of effort. The pupil-response results reflect these individual differences [*see lower illustration on opposite page*] and also show a fairly consistent increase in dilation as the problems increase in difficulty. Individual differences of another kind are revealed by the trace of a subject's pupil size. Most subjects do have a response that drops to normal as soon as they give the answer. In some people, however, the size of the pupil decreases momentarily after the answer is given and then goes up again, sometimes as high as the original peak, suggesting that the worried subject is working the problem over again to be sure he was correct. Other people, judging by the response record, tend to recheck their answers before announcing them.

We have found a similar response in spelling, with the maximum pupil size correlated to the difficulty of the word. The response also appears when a subject is working an anagram, a situation that is not very different from the kind of mental activity associated with decision-making. We believe the pupil-response technique should be valuable for studying the course of decision-making and perhaps for assessing decision-making abilities in an individual.



ATTITUDE CHANGES are revealed by responses to Johnson (*left*) and Goldwater (*right*) before (*light bars*) and after (*dark bars*) subjects read a statement supplied by the experimenter. Nonpolitical material had no appreciable effect. The anti-Johnson material had the expected effect. Bitter anti-Goldwater material made response to both candidates negative.

It is always difficult to elicit from someone information that involves his private attitudes toward some person or concept or thing. The pupil-response technique can measure just such attitudes. We have established that the correlation between a person's expressed attitude and his "measured pupil" attitude can vary widely, depending on the topic. For example, we tested 64 people with five pictures of foods and also asked them to rank the foods from favorite to least preferred. When we matched each person's verbal report with his pupil response, we obtained 61 positive correlations—a result one could expect to get by chance only once in a million times.

The correlation is poor in an area that involves social values or pressures, however. For example, we do not get such good agreement between pupillary and verbal responses when we show women pictures of seminude men and women. Nor did we get good correlation when we did a political study last fall. We showed photographs of President Johnson and Barry Goldwater to 34 University of Chicago students, faculty members and employees. Everyone professed to be in favor of Johnson and against Goldwater. The pupil-response test, however, had indicated that about a third of these people actually had a slightly more positive attitude toward Goldwater than toward Johnson.

To be sure, the pupil test may overemphasize the effect of physical appearance; certainly our data do not prove that a third of the subjects went on to vote for Goldwater. But the results do raise the interesting possibility that at least some of them did, and that in the liberal atmosphere of the university these people found it difficult to utter any pro-Goldwater sentiment. The results suggest that our technique, by which we measure a response that is not under the control of the person being tested, may yield more accurate representations of an attitude than can be obtained with even a well-drawn questionnaire or with some devious "projective" technique in which a person's verbal or motor responses are recorded in an effort to uncover his real feelings.

For me the most interesting aspect

TWO PHOTOGRAPHS, almost identical, elicited very different responses from a group of male subjects. One in which a girl's eyes were retouched, as at left, to make the pupils large got a greater response than one in which the pupils were made small (*right*).

of our work has been the measurement of changes in attitude. We begin by determining the pupil response of one of our volunteers to someone's picture. Then we have the subject read some kind of informative material, we retest for the response and compare the "before" and "after" scores. In one case the reading material consisted of a passage indicating that the man whose picture had been displayed was the former commandant of the concentration camp at Auschwitz. When we then remeasured the subject's pupil response to the man in question, we found that a more negative attitude had clearly developed as a result of the intervening reading.

Take another and more hypothetical example: Suppose a patient seeking psychotherapy has a fear of people with beards. We ought to be able to get a pupillary measure of his attitude by showing him photographs of bearded men, among others, and then be able to check on the course of treatment by repeating the test later. Regardless of whether what intervenes is straightforward information, psychotherapy, political propaganda, advertising or any other material intended to change attitudes, it should be possible to monitor the effectiveness of that material by measuring changes in pupil size, and to do this with a number of people at any desired interval.

One recent study along these lines will illustrate the possibilities. We showed five different photographs of President Johnson and five of Goldwater, along with a single photograph of former presidents Kennedy and Eisenhower, to three groups of people. One group thereupon read anti-Johnson material, another read anti-Goldwater material and the third read some excerpts from a psychology journal that had no political content. Then each group was retested.

Now the people who had read the anti-Johnson material showed a slightly smaller response than before to Johnson and a slightly larger response than before to Goldwater. Some extremely negative anti-Goldwater material, which one of my assistants apparently found very easy to write, had a different kind of effect. It did cause the expected decrease in the response to Goldwater, but it also caused a large drop in the response to Johnson and even to Eisenhower! The only person who was unaffected was Kennedy. This may indicate that bitter campaign propaganda can lower a person's attitude toward politicians in general, Kennedy alone being spared for obvious reasons.

The pupil response promises to be a new tool with which to probe the mind. We are applying it now in a variety of studies. One deals with the development in young people of sexual interest and of identification with parents from preschool age to high school age. In an attempt to establish personality differences, we are tabulating the responses of a number of subjects to pictures of people under stress and pictures of the same people after they have been released from the stressful situation. Our other current study deals with volunteers who are experiencing changes in perception as the result of hypnotic suggestion. In the perception laboratory of Marplan, a communications-research organization that has supported much of our work, Paula Drillman is studying responses to packages, products and advertising on television and in other media. Several laboratories at Chicago and elsewhere are employing our techniques to study such diverse problems as the process of decision-making, the effect of certain kinds of experience on the attitudes of white people toward Negroes and the efficacy of different methods of problem-solving. Those of us engaged in this work have the feeling that we have only begun to understand and exploit the information implicit in the dilations and constrictions of the pupil.

Kodak reports on:

high-priced drudgery diminished . . . facts to bring to a plastic-picking meeting . . . something new and primitive

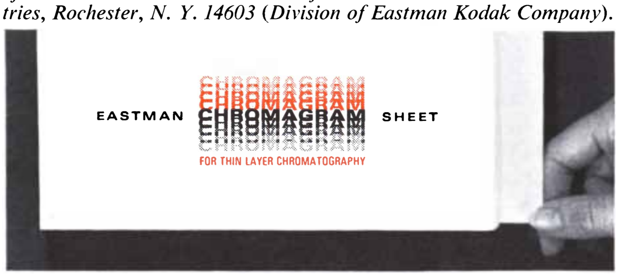
Thin-layer chromatography caught on about four years ago. Now anybody who claims knowledge of how to identify or synthesize substances and finds himself vague about TLC should worry a little. He has been washed up from the mainstream and had better take measures. He will not read far or listen long before the thought strikes that he should learn the technique for coating slurries of adsorbents like silica gel on glass plates. At chemical and biological labs the world around, a goodly chunk of the working time is now devoted to this art. Many fine tricks influence the homogeneity and isotropy of the coating and the level of activation imparted to it. No sooner having learned of them, he can now forget them.

He is just as well off as the eager beavers who couldn't wait until the messiness was eliminated by us, who got our start 85 years ago in relieving photographers of the need to coat their own plates.

Now we have a mighty force of chemists and respected technicians of our own. During recent months doubts have been deftly planted in their minds about the wisdom of drawing pay for such essentially mindless tasks as coating their own chromatoplates, except where some special technique still demands glass or an adsorbent other than silica gel bound with polyvinyl alcohol and made fluorescent by incorporation of Ca_2SiO_3:Pb,Mn. They have been persuaded to weigh the importance of these special techniques against costs of preparing glass chromatoplates, of documenting the results shown by the chromatogram, of storing the bulky things for reference, of recovering the expensive edged glass for reuse.

For general work they have begun to standardize on a poly(ethylene terephthalate) sheet on which 100μ of fluorescent, PVA-bound silica gel of our own preparation and control has been coated, not manually but by a manufacturing organization that owes its robust health largely to its precision in depositing thin layers of one thing on another.

As EASTMAN CHROMAGRAM *Sheet, this new polyester TLC medium—scissors-prone, conveniently flexible but not limp, unbreakable, sending up no clouds of siliceous dust to breathe—can now be obtained from a nearby lab supply house. If the price they quote for a box of twenty 20cm x 20cm sheets does not bring pangs of guilt about continuing to coat by hand, your problem is obviously one of excess staffing. If you hesitate only because you want to try it first, request a sample of* EASTMAN CHROMAGRAM *Sheet from Distillation Products Industries, Rochester, N. Y. 14603 (Division of Eastman Kodak Company).*



Lightness and toughness through orderliness

A person who is expected to know a lot should be able to answer a simple question like "What commercial plastic has the lowest density without resorting to bubbles?"

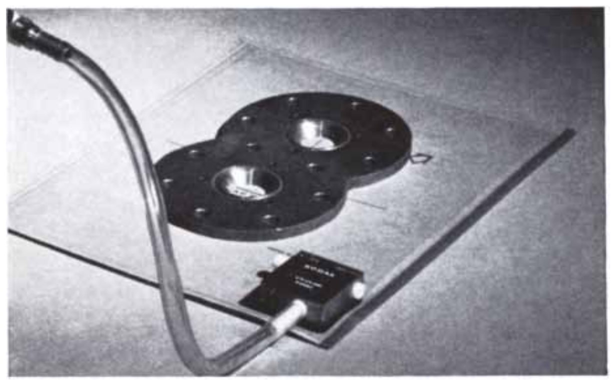
He will reply, "TENITE Polyallomer."

A short colloquy will ensue. The disputants will then adjourn to the library. There none of the chemical dictionaries will be found to define "polyallomer." Of course not. We coined the word too recently. Had to. Human race had had little if any previous need to refer to a hydrocarbon high polymer that preserves its highly ordered arrangement without fixed proportionality between the ethylene and propylene moieties that polymerized into it. Hard to understand but easy to appreciate because 1) it beats polypropylene in lightness of weight, impact strength, melt strength, abrasion resistance, defiance of flexing fatigue ("hingeability"), low brittleness temperature, less notch sensitivity, stronger welds, free flow at lower molding temperatures with less strain freezing into large sections; 2) it beats linear polyethylene in lightness of weight, dimensional stability, surface hardness, higher softening point, lesser and more uniform mold shrinkage.

Now a further consideration commends TENITE Polyallomer to a group sitting down to decide whether they want to build something out of it: nothing more or less important than quantitative data on its chemical resistance. For a year we have kept samples of two formulations of the plastic in 42 different liquids at 73°F.

Technical Report TR-18, from Eastman Chemical Products, Inc., Kingsport, Tenn. 37662 (Subsidiary of Eastman Kodak Company) tells how they made out. No harm in asking other questions about TENITE *Polyallomer that come to mind.*

The KODAK Vacuum Probe



The tube leads to ½ atmosphere of vacuum. The metal object is to be radiographed for soundness. X-rays from above will traverse it to the sheet of high-definition x-ray film in the envelope beneath it. The square object is a KODAK Vacuum Probe.

Though a vacuum probe sounds like a device that everybody but you has been familiar with for years, such is not the case. We have just invented it. Moving fast, we are now ready to stock x-ray dealers with it.

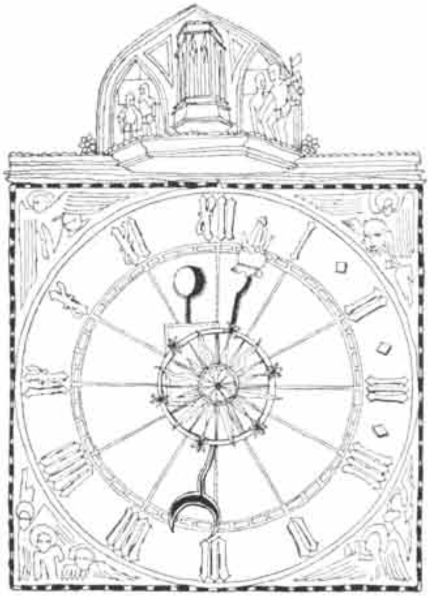
Little demand would be felt for this vacuum probe were there not contained in the envelope sheets of paper lightly but uniformly coated with lead oxide facing the film emulsions. Such an envelope is designated KODAK Industrial X-ray Film, LEAD PACK. The primary radiation that gets through generates photoelectrons in the lead oxide. These can strengthen the image when they hit the film, provided they don't have so far to go as to put halos around the details, ruining the idea.

Therefore when you press one of the white buttons on the gimmick, a tiny hollow needle pierces the envelope. In a moment the lead oxide and the radiographic emulsion are sucked close together. After exposure the other white button detaches the vacuum probe. Then the envelope is opened in the darkroom and the film processed.

A new and useful device this primitive has to have a name that sounds scientific and old-hat at the same time.

This is another advertisement where Eastman Kodak Company probes at random for mutual interests and occasionally a little revenue from those whose work has something to do with science

SCIENCE AND



Transport for the Corridor

A first step toward the radical improvement of intercity public transportation has been taken by the Johnson Administration with a request to Congress for $20 million to begin a program of research and development. The proposal appears to reflect a conclusion by the Administration that many problems of urban congestion and decay can be successfully attacked only with increased Federal initiative and help. Presumably state and regional efforts would be restricted on the one hand by limited jurisdiction and on the other by the difficulty of enlisting the cooperation of the many municipal governments involved.

In his proposal to Congress, President Johnson emphasized ground transportation. He also spoke of "an imminent need for improved intercity transportation in the densely populated area along the East Coast—between Washington and Boston—where travel is expected to increase by 150 to 200 percent between 1960 and 1980." This Northeast Corridor, as it is sometimes called, is heavily urbanized: it contains 20 percent of the U.S. population in only 2 percent of the nation's geographical area. The corridor is therefore expected to be the principal laboratory for testing improvements in ground transportation, although (as the President pointed out) any ideas that succeeded there would also be applicable to other parts of the country where high-speed transport is needed.

Some of the ideas being considered in the Department of Commerce, which will effectuate the President's proposal, would introduce modes of ground transport so different from existing systems that they are sometimes given the name "guideways" to distinguish them from railways and highways. For example, an idea that has been put forward in the aerospace industry is to use a tunnel in which a partial vacuum would be maintained to reduce the air resistance to fast passenger vehicles; one proposal would use the same pumps that evacuated air from the tunnel to provide propulsion for the vehicles. Another idea envisions an enclosed tube in which capsules would be propelled at 200 miles per hour by fluid jets. There are suggestions that vehicles could ride on cushions of air or liquid instead of on tracks or roadbeds. An objective common to many of the proposals is providing a means of attaching capsules to and detaching them from the main vehicle while that vehicle continues to move at high speed; in that manner a guideway could serve local stations without delaying the through vehicle.

Apart from these imaginative ideas there is some talk of attempting to improve existing railroads so that passenger trains could run consistently at speeds above 100 miles per hour. Transportation experts tend, however, to regard the possibilities in that direction as limited. They believe that significant improvements in ground transportation will require new technologies.

Lost Force

The speculation that there may be a very weak, long-range fifth force in nature in addition to the four known forces (nuclear, electromagnetic, weak and gravitational) has been brought to an end by experiments conducted in Britain and Switzerland. The fifth force had been proposed to save the principle of time-reversal invariance: the concept that nature is indifferent to the direction in which time is flowing.

The principle had been placed in jeopardy by an experiment carried out last year at the Brookhaven National Laboratory by Val L. Fitch, James H. Christenson, James W. Cronin and René Turlay of Princeton University. They found that two times out of 1,000 the K_2^0 (K-two-zero) meson decays into two pi mesons (π^+ and π^-) instead of three pi mesons. The two-pi decay violates the "*CP*" rule, which states that particle reactions are indistinguishable from their antimatter mirror images. In this rule *C* (for charge conjugation) refers to matter-antimatter symmetry and *P* (for parity) to mirror-image symmetry. The K_2^0 meson has a *CP* value of -1, whereas π^+ and π^- have a combined *CP* of $+1$. The decay of K_2^0 into π^+ and π^- means that a state with a *CP* of -1 has changed into a state with a *CP* of $+1$. Although unexpected, this violation can be tolerated if an expanded rule, the *CPT* rule, remains valid. Here *T* stands for time-reversal symmetry. A violation of *CP*, therefore, implies a corresponding violation of *T*—unless, of course, a new principle is at work.

The fifth force was such a principle. Proposed independently last summer by two groups of physicists, it was conjectured to be a force that would have one sign if produced by ordinary matter and an opposite sign if produced by antimatter. Since our galaxy presumably consists entirely of ordinary matter, the potential of fifth-force energy at the earth's surface should be predominantly of one sign. Such an asymmetrical force field would show up by converting an occasional K_2^0 meson into a K_1^0 meson, which has a *CP* value of $+1$ and therefore can decay into two pi mesons without violating the *CP* rule.

There was a simple test for the presence of the new force. If it existed, the percentage of K_2^0 mesons decaying into two pi's should increase as the square of the meson energy. This experiment has now been performed and the result is negative: the percentage of K_2^0 mesons decaying into two pi's is constant for meson energies ranging from one billion to 10 billion electron volts. One of the experiments was conducted at the European Organization for Nuclear Research (CERN) in Geneva and the other at the Atomic Energy Research Establishment at Harwell in England.

Theorists appear to have reluctantly concluded that time-reversal symmetry is indeed violated in some fashion by the K_2^0 decay. The exact nature of the violation still calls for an explanation. A variety of complex hypotheses are being discussed, along with proposals for testing them. The situation is murky and disturbing.

Chemical Lasers

Recent development of a "chemical laser" fulfills a prediction made in 1961 by J. C. Polanyi of the University of Toronto and also has provoked a small argument over definition of the term itself. Laser, of course, stands for "light amplification by stimulated emission of radiation." The light waves emitted by a laser are coherent, meaning all in step, and are limited to virtually a single wavelength. All the early lasers used electricity or light for "pumping," that is, for providing the energy needed to raise atoms in an active medium to an excited state. The active medium can be a crystal (such as a ruby), a rarefied gas (such as neon mixed with helium) or even a glass (such as neodymium in borate glass).

The problem in designing a laser is to produce an "inverted" population of excited atoms in which there are more atoms in a particular excited state than in the "ground" state. Once this is done a chain reaction is easily triggered: in response to a photon of the right energy the excited atoms release a cascade of photons of the same energy, producing an intense coherent beam of visible light or infrared radiation. The emitted radiation may be either continuous or pulsed, depending on the type of laser.

The distinguishing feature of the chemical laser, according to one definition, is that the energy for pumping is provided by a chemical reaction rather than externally supplied electricity or light. Electricity or light, however, may be required to initiate the chemical reaction. In this definition the key feature is that the pumping energy comes from the making or breaking of a chemical bond. Four years ago Polanyi described a chemical reaction involving hydrogen and chlorine that seemed likely to produce laser action in the infrared region of the spectrum.

A laser employing this chemical reaction has been described in *Physical Review Letters* by Jerome V. V. Kasper and George C. Pimentel of the University of California at Berkeley. Their laser is a 60-centimeter glass tube containing one part of chlorine and two parts of hydrogen at reduced pressure. In response to an intense flash of light the two gases react to form hydrogen chloride (HCl) and atomic chlorine (Cl). The HCl molecule leaves the reaction in a vibrationally excited state and on decaying to a less energetic state provides the photons for laser action. The infrared radiation emitted is centered near 3.8 microns, a wavelength roughly 10 times longer than that of blue light. The Kasper-Pimentel laser is apparently the first in which laser action is produced by the chemical reaction of two different substances.

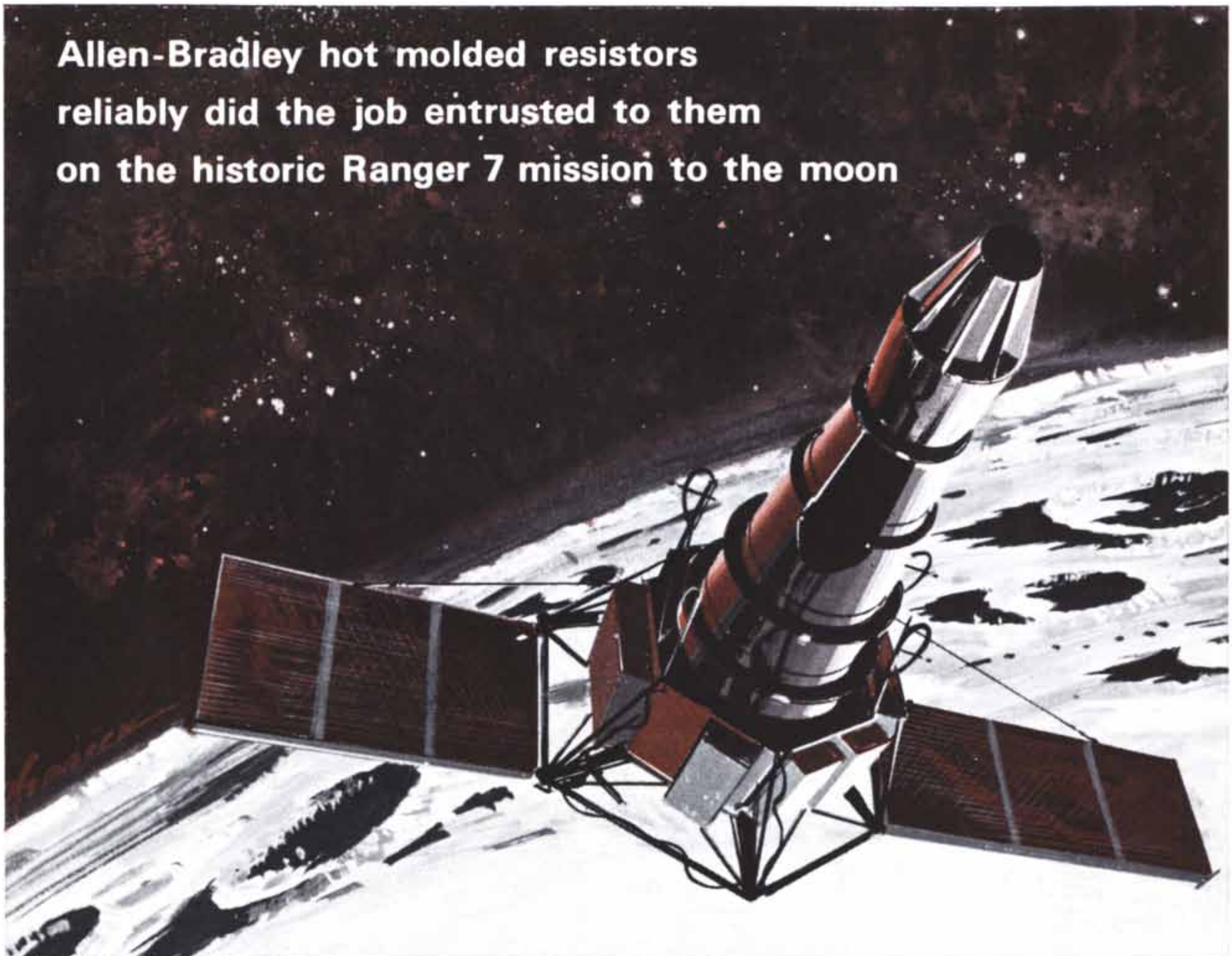
Earlier lasers, however, can be regarded as chemical if the only requirement is that the pumping energy be supplied by the making or breaking of a chemical bond. For example, at the Bell Telephone Laboratories, C. K. N. Patel and his co-workers have obtained laser beams from a variety of simple gases and gas mixtures in which the photons are also emitted by vibrationally or rotationally excited molecules rather than by electronically excited atoms. Although the primary energy of excitation in Patel's lasers is supplied by an electric discharge, the final pumping energy is provided, in some cases, by the formation of a chemical bond.

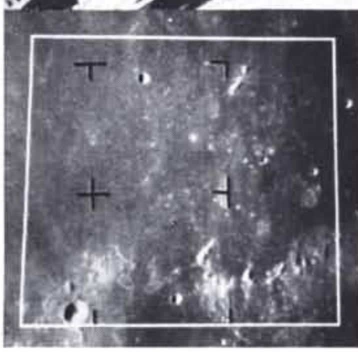
Some workers feel that the term "chemical laser" should be reserved for a device in which the chemical reaction is self-sustaining. Such a laser is feasible in principle but has not yet been built.

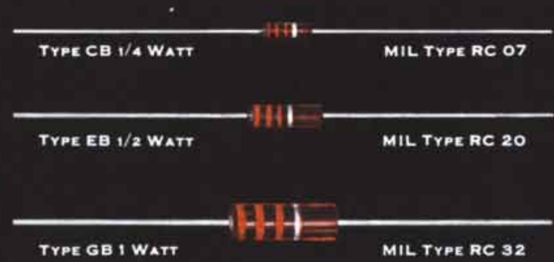
Perhaps the most unusual laser employing bond breakage and formation is one announced last year by A. Crocker, H. A. Gebbie, M. F. Kimmitt and L. E. S. Mathias of the Services Electronics Research Laboratories in England. Their laser contains nothing but water vapor activated by an electric discharge. It has produced coherent radiation at more than 20 different wavelengths in the infrared. The energy transitions that account for all of them have not yet been identified. In addition to providing wavelengths of interest and potential utility, the new lasers promise to yield knowledge about the energetics of chemical reactions.

Poverty as a Cause of Death

Poverty is itself a cause of death, according to George James, New York City Commissioner of Health. In his year-end report for 1964 James compared statistics on deaths in four low-income and four high-income areas of the city. Infant mortality was more than twice as high in the poor sections as in the well-to-do sections, maternal mortality was seven times as high and the death rate from tuberculosis was five times as high. In a speech to the American Public Health Association, James reported on a study of 1960–1963 death rates in Flushing, a middle-class section of Queens, and in Bedford, a poor







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■ The highly successful journey of Ranger 7 to the moon, which produced 4304 photographs of the lunar surface, was a brilliant scientific accomplishment. The "quality" of Allen-Bradley hot molded resistors warranted their selection for this tremendously important space probe. Certainly, the faith of the Ranger 7 engineers in the reliability of these components was justified.

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section of Brooklyn. The statistical disadvantage of the poor turned out to be nonspecific: "The leading causes of death all cause higher death rates in our poorer sections." Statistics were compared for cardiovascular and kidney disease, cancer, diabetes, pneumonia and influenza, and accidents—all causes for which death rates tend to vary much less than they do for infant and maternal mortality and tuberculosis. In each the death rates were higher in Bedford and lower in Flushing than they were for the city as a whole.

If New York could maintain its overall health record at the Flushing level, James said, there would be 13,000 fewer deaths a year in the city. "It is no exaggeration to say that these deaths are caused by poverty." If poverty is looked on as the actual "cause" of these "preventable" deaths, he pointed out, it can be considered the third-ranking cause of death in the city.

Precambrian Flora

The microorganisms preserved in a two-billion-year-old outcrop of Precambrian rock along the northern shore of Lake Superior have long been recognized as the world's oldest fossils; a recently completed analysis reveals that most of them are the remains of alga-like photosynthetic plants. Reporting in *Science* on more than a decade's study of the fossil-rich Gunflint cherts of Ontario by the late Stanley A. Tyler and himself, Elso S. Barghoorn of Harvard University has described eight hitherto unknown genera of organisms that flourished in the shallow waters of that region in Middle Precambrian times. Seven of the eight were almost certainly plants analogous to, although not related to, the various photosynthetic blue-green algae that inhabit aquatic environments today. The eighth, a more advanced organism, remains an enigma. In basic organization it is reminiscent of such coelenterates as the hydra, but its tiny size—some 30 microns in length at a maximum—seems to rule out its admission to that phylum of the animal kingdom.

The Gunflint fossils owe their preservation to an unusual sequence of events. The waters they inhabited were evidently rich in dilute silica; when unknown causes precipitated this silica as a gel, the organisms were entrapped. Eventually transformed into the mineral opal through dehydration, the former gel provided its chance enclosures with the protection of an almost incompressible matrix. This matrix crystallized into

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RIDE WALT DISNEY'S MAGIC SKYWAY AT THE FORD MOTOR COMPANY PAVILION, NEW YORK WORLD'S FAIR the chalcedony and quartz of which the Gunflint cherts are composed but escaped the kind of metamorphosis under heat and pressure that has apparently destroyed the fossil content of most other Precambrian sediments. Commenting on this accident of preservation, Barghoorn writes: "[It is] a window through the Precambrian metamorphic veil."

Hybrid Cells of Mouse and Man

A means of combining the living cells of mice and men so that the resulting cells contain two or more nuclei from both species has recently been achieved by investigators at the University of Oxford. In nature such multinuclear cells are found only among primitive plants of the fungus group; they are used in studies that explore the relations between the cell nucleus and its surrounding cytoplasm. The fact that similar studies can now be conducted with animal cells opens up a new province of zoological investigation.

As reported in *Nature,* the starting point for Henry Harris and J. F. Watkins was the knowledge that one strain of influenza virus, when added to a suspension of single cells from a mouse tumor, made some of the cells fuse. A second variety of mammalian cell, originally derived from a human cancer, was available to the investigators; a mix of the two suspensions together with the influenza virus resulted in fusion of about 10 percent of the cells, some of which ended up with as many as 20 nuclei. Using substances labeled with a radioactive isotope, Harris and Watkins established that the nuclei continued to synthesize both deoxyribonucleic acid (DNA) and ribonucleic acid (RNA) for a number of days and that the cells also synthesized protein.

One conclusion already reached concerning the relations between the nucleus and the cytoplasm in mammalian cells is that whether or not the nucleus synthesizes DNA is not a matter solely determined by events in the cytoplasm; Harris and Watkins found DNA synthesis progressing in some nuclei at the same time that others were inactive, although both groups obviously shared the same cytoplasm.

Anti-heroin

What keeps an addict addicted—his physiological need for narcotic drugs or his psychological need for the euphoria they produce? Both, apparently, and this is why traditional cures

Almost an electrometer? The new all-silicon Model P2A Differential Operational Amplifier edges one decade closer to the electrometer range than the famous Philbrick Model P2, *at no increase in cost.*

DESCRIPTION

The new Philbrick P2A can be used as an electrometer to measure currents less than 10^{-12} amperes routinely, yet it exhibits unusual voltage stability. Briefly, it is an all-silicon, solid-state, high gain differential operational amplifier with no inherent common mode error and with fully floating input. Model SP2A is a plug-in amplifier with the same circuit as the P2A but has the additional benefit of guarded inputs. The P2A is mounted in a die-cast aluminum case measuring $4\frac{1}{16}''$ x $1\frac{5}{16}''$ x $1\frac{11}{16}''$. Model SP2A is wired on an etched-circuit glass board with 15-terminal gold-nickel edge connectors and shielded by an exoskeletal nickel-plated steel case measuring $3\frac{3}{16}''$ x $1\frac{1}{2}''$ x $2\frac{3}{8}''$.

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TYPICAL INPUT OFFSET CURRENT .... $< 10^{-12}$ amp.

INPUT IMPEDANCE (to common) $> 10^{12}\ \Omega$

CURRENT NOISE .... $< 10^{-13}$ amp.

OUTPUT ....2 ma at $\pm$ 10 V

TYPICAL VOLTAGE OFFSET (0°C to 65°C) ....3 mV

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PRICE ....$227.00 each (1-4)

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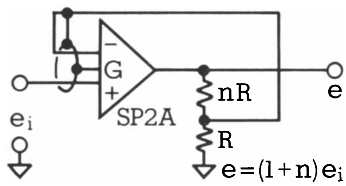
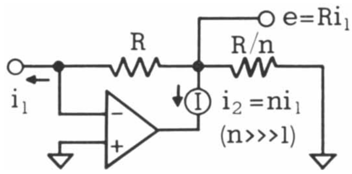
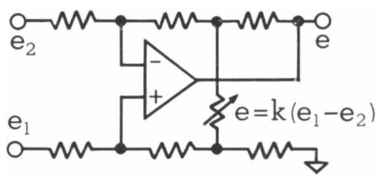


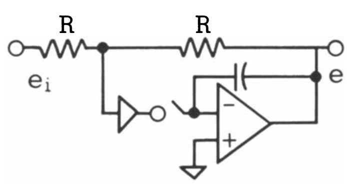
FOLLOWER-AMPLIFIER



CURRENT AMPLIFIER
CURRENT-TO-VOLTAGE TRANSDUCER



ADJUSTABLE-GAIN SUBTRACTOR



TRACK-AND-HOLD CIRCUIT

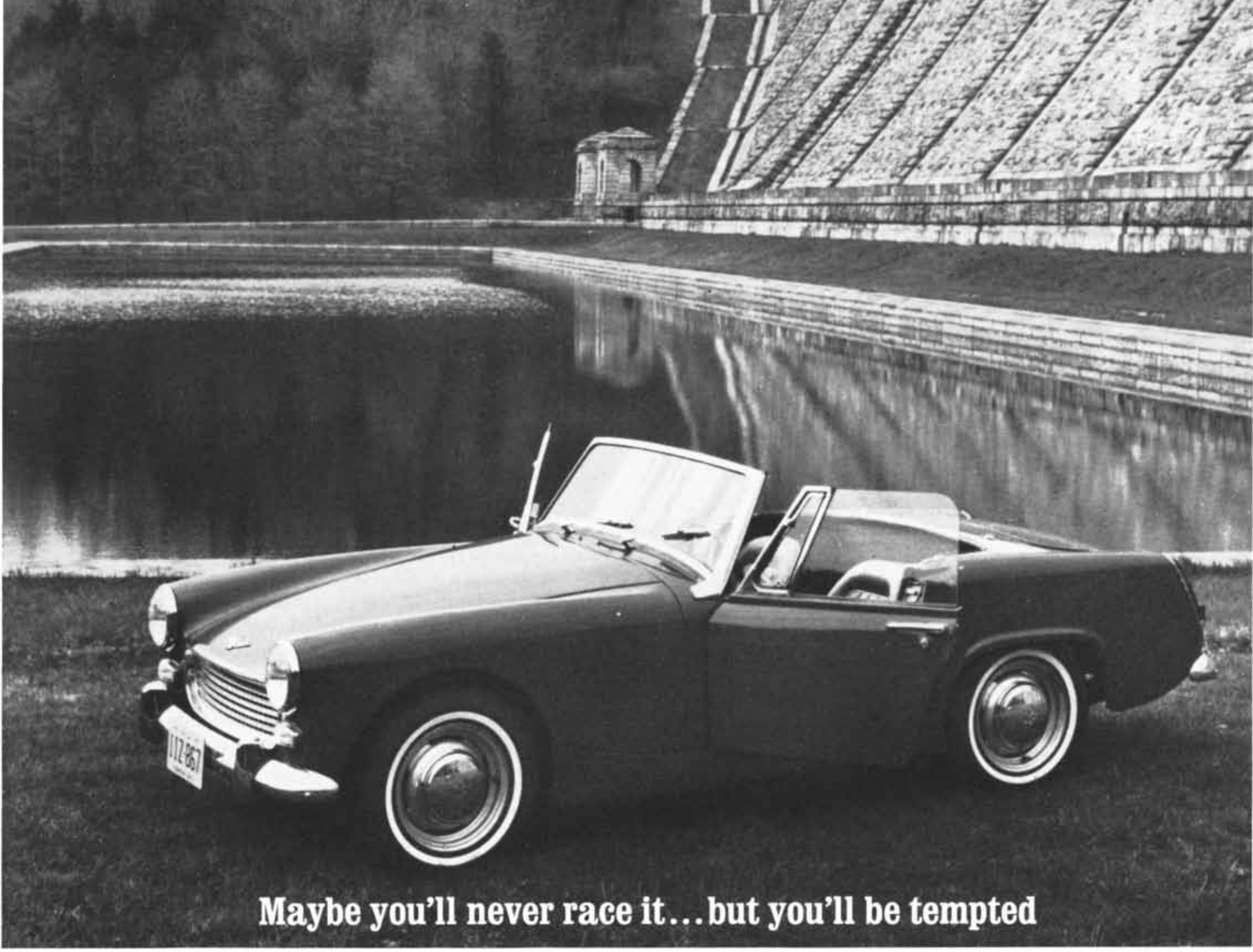
See this and other Philbrick products at the FASEB meeting, Booth V16 that meet only one or the other need are generally unsuccessful. Now Vincent P. Dole of the Rockefeller Institute has reported promising results from experiments with a drug that simultaneously meets the physiological need of the addict and blocks any attendant euphoria.

Dole has induced several heroin addicts hospitalized at the Institute to take methadone, a drug that reduces withdrawal distress. Methadone does not produce the "high," or euphoria, brought on by heroin; indeed, a strong enough dose of methadone makes the subsequent intake of heroin incapable of producing a "high." Thus the addict who has received methadone is deprived of his euphoria but does not suffer the agony usually associated with such deprivation.

Methadone is a synthetic compound developed in Germany more than 25 years ago and used in Europe today as an ordinary analgesic. Over the years experimenters have used it as a transitional drug for addicts attempting to overcome their dependency on heroin. Dole, who has administered methadone to his group of patients in quite large dosages, is the first to report significant results. His studies indicate that, unlike heroin, methadone need not be taken in increasing dosages to produce the same effect; moreover, it causes no behavioral change. More research is planned to determine the safe upper limits of methadone intake.

Shrinking Nucleus

Until recently our galaxy was thought to be a rather tightly wound spiral with a large nucleus, or bulge, at its center. According to the classification system devised by Edwin P. Hubble in 1926, it was designated an Sb spiral galaxy, similar in size and shape to the nearby Great Nebula in Andromeda. It now appears that the nucleus of our galaxy is much smaller than had been supposed; photoelectric measurements of the brightness of certain stars near the galactic center indicate that the nucleus is roughly 6,500 light-years across, or only about half the size of the Andromeda nebula's nucleus. The new measurements support the view that our galaxy should be reclassified as a more open Sc spiral rather than a tight Sb one. The measurements were made by Halton C. Arp of the Mount Wilson and Palomar Observatories with the 200-inch Hale telescope. Arp reported his findings in a recent issue of the *Astrophysical Journal.*



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Intense Magnetic Fields

Continuous fields as strong as 250,000 gauss, 500,000 times the strength of the earth's magnetic field, have been generated at the National Magnet Laboratory

by Henry H. Kolm and Arthur J. Freeman

From time to time in the history of science a particular experimental problem engages the interest of workers from several disciplines. The problem may be a common obstacle in the way of entirely different lines of inquiry, or it may be a new technique whose development promises to open unexplored territories to investigation. In either case, a new subdivision of science often comes into being to coordinate the diverse capacities and objectives of the interested parties. After a temporary but exciting existence the original problem is solved and the subdivision loses its *raison d'être;* it is reabsorbed into the disciplines that gave rise to it. One example of such a subdivision is cryogenics, or low-temperature physics, which is in the process of completing its life cycle. The study of matter under the influence of intense magnetic fields, and the associated problems of generating such fields, constitute another subdivision that is just entering the main phase of a similar cycle.

The need for more intense magnetic fields to serve as extreme research environments is shared by almost all the major divisions of physics: high-energy physics, plasma physics, solid-state physics, geophysics and even biophysics. In many ways the need for more intense fields is akin to the need for larger astronomical telescopes: both represent an increase in resolution, or the capacity to distinguish fine details. Although the first steps toward overcoming the technical difficulties involved in generating intense magnetic fields were taken some 30 years ago, this task has only recently attracted the kind of widespread attention and support that has characterized the success of other large-scale scientific undertakings, such as the construction of telescopes, particle accelerators, nuclear reactors and large computers. The first comparable venture in the generation of intense magnetic fields was begun in 1963 with the dedication of the National Magnet Laboratory at the Massachusetts Institute of Technology. The new laboratory is a cooperative research facility supported by the U.S. Air Force Office of Scientific Research and available to the entire scientific community. Similar institutions are being planned in France, Great Britain and the U.S.S.R. Clearly a golden age of intense-field research is at hand. It is significant that even at this early stage man has come closer to outdoing nature in the generation of intense magnetic fields than in the creation of any other environmental extreme.

The Four Basic Magnetic Effects

A magnetic field can be best understood in terms of the four basic effects by which it manifests itself: (1) A homogeneous stationary field exerts a torque, or twisting force, on a magnetic dipole. (2) A homogeneous stationary field exerts a deflecting force on a moving electric charge. (3) A field in which the lines of force diverge, or otherwise vary in space, exerts a force on a magnetic dipole. (4) A field that varies in time exerts a force on a stationary electric charge [*see upper illustrations on pages 68 and 69*].

The most familiar example of a magnetic dipole is a compass needle; by observing its alignment with respect to the earth's magnetic field William Gilbert was able to conclude in 1600 that the earth is itself a giant magnetic dipole. Much later it was learned that a circulating electric current behaves like a magnetic dipole, and that the magnetism of a compass needle is caused by the more or less parallel alignment of a large number of atomic dipoles, each consisting of a tiny circulation of electric current. In fact, all the magnetic fields that have ever been observed are dipolar in nature and can be attributed to circulating electric charges. Theoretically monopoles, or single magnetic poles, should exist, but none has ever been observed [see "Magnetic Monopoles," by Kenneth W. Ford; SCIENTIFIC AMERICAN, December, 1963].

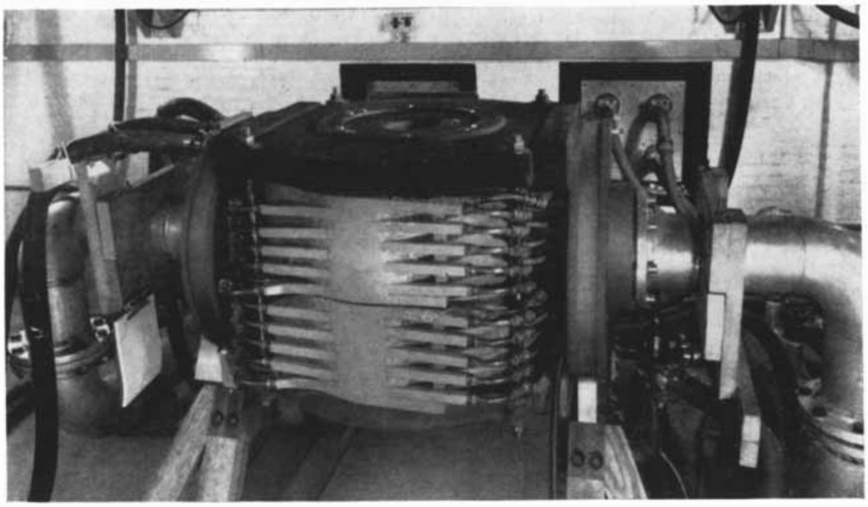
The circulating current in an atomic dipole consists of spinning or orbiting charged particles (protons or electrons). Since there is a circulating mass, or angular momentum, associated with the circulating current, an atomic dipole acts like a tiny gyroscope: it does not align itself perfectly parallel to an applied magnetic field but precesses, or wobbles, around a line of force in the field at a characteristic frequency. The synchronous precession of all the identical atomic dipoles in a solid constitutes the macroscopic effect known as a magnetic resonance [see "Magnetic Resonance," by George E. Pake; SCIENTIFIC AMERICAN, August, 1958]. The resonance frequency, or the frequency at which the solid will absorb electromagnetic radiation, is proportional to the intensity of the applied magnetic field. In the intensity range accessible to conventional laboratory magnets the resonance frequency is in the microwave region of the electromagnetic spectrum; more intense magnetic fields can force this frequency up into the infrared region. In crystalline substances the resonance frequency depends on a complex interaction of atomic dipoles. As a result much of our knowledge about atomic dipoles and their interactions has been gathered from observations of magnetic resonance.

Another important magnetic technique based on the alignment of atomic dipoles by an applied magnetic field is the attainment of very low temperatures by the process of adiabatic, or thermally isolated, demagnetization [*see illustration on page 70*]. In some magnetic substances—for example certain salts—the interactions of the spinning electrons are so weak that the neighboring atomic dipoles do not become aligned like the dipoles in a compass needle. Instead they tend to behave independently of one another. Such substances are called paramagnetic.

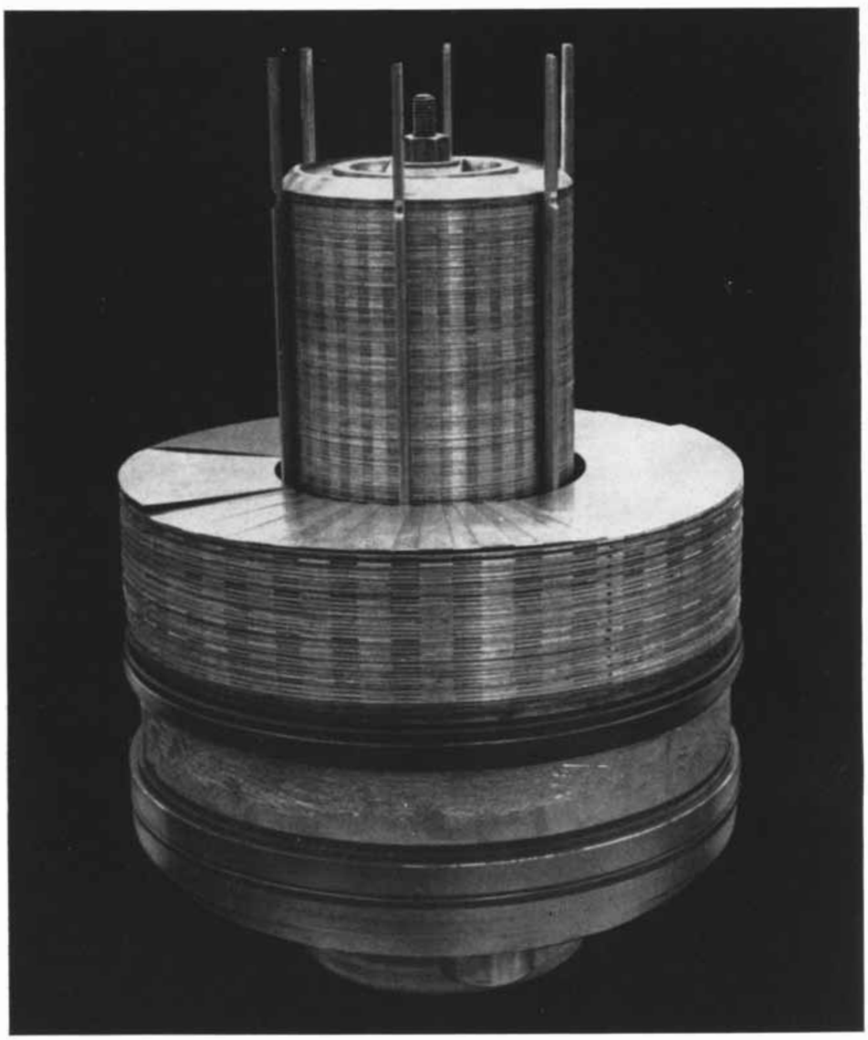
The random oscillation of magnetic dipoles in a paramagnetic salt constitutes part of its thermal, or heat, energy. When an applied magnetic field is strong enough to force the dipoles in such a salt into partial alignment, some of the thermal energy is forced into other types of vibration and the salt is observed to heat up. If the magnetic field is maintained, one can remove all of this thermal energy and cool the salt to the lowest temperature attainable by the most effective conventional means, namely the forced evaporation of a liquid-helium bath.

After cooling the salt to a temperature of about 1 degree Kelvin (1 degree centigrade above absolute zero) one can isolate it from the helium bath by evacuating the surrounding space. Then the magnetic field is turned off. The paramagnetic dipoles will resume their random orientations, extracting energy from other types of thermal motion. In this way the salt can be cooled to small fractions of a degree Kelvin; the stronger the applied magnetic field, the lower the final temperature. The process of adiabatic demagnetization strikingly demonstrates certain statistical laws of physics, which state that randomness will assert itself even at the expense of energy, and that energy is required to impose order. The capacity of a magnetic field for inducing a high degree of order is one of its most useful characteristics.

The second effect by which a magnetic field manifests itself, namely exerting a force on a moving electric charge, is distinguished by the fact that the force always acts at right angles to the direction of motion of the charge. It is this property that allows the manipulation of charged particles by applied magnetic fields. For example, magnetic fields are employed in television tubes and electron microscopes to deflect and focus electron beams, in particle detectors and mass spectrographs to separate and distinguish between particles of



250,000-GAUSS SOLENOID MAGNET at the National Magnet Laboratory is capable of generating the most intense continuous magnetic fields attainable. Outermost section of hollow, square copper windings is visible in this recent photograph. Magnet contains three tons of copper and has an outside diameter of 36 inches. At full power it consumes 16 million watts of electricity and 2,000 gallons of water per minute. Diameter of bore is two inches.



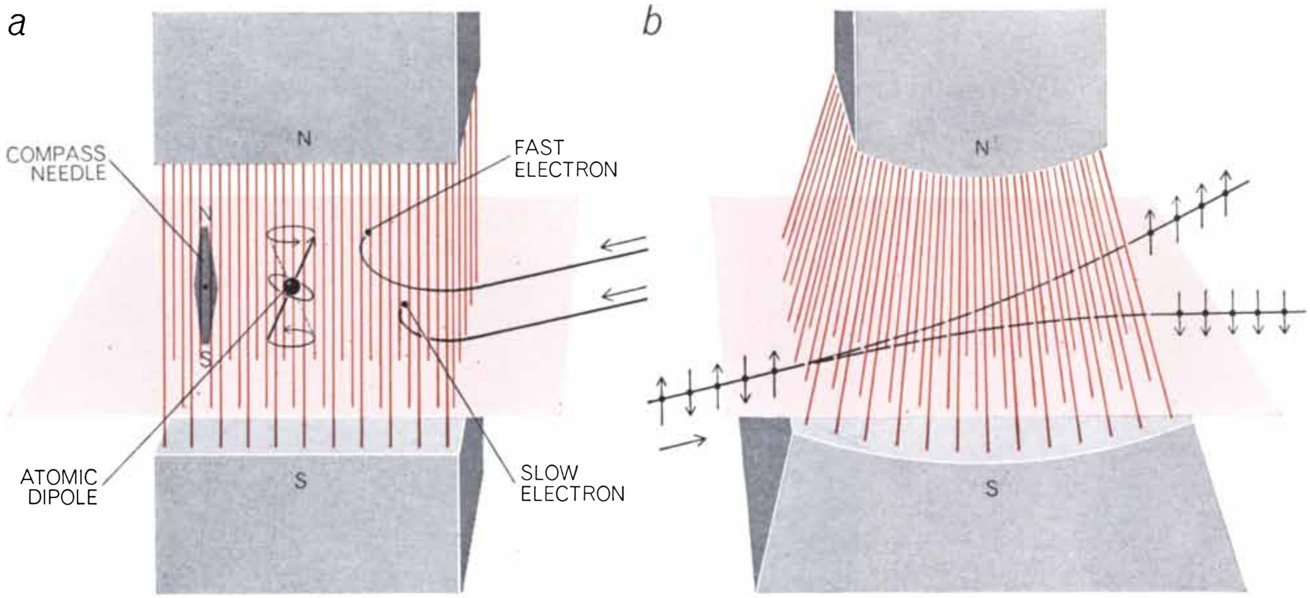
TWO INNER SECTIONS of the 250,000-gauss magnet were photographed during construction a year ago. In each section copper and mica plates were interleaved to form a continuous copper helix. Radial channels transmit water for cooling. Innermost plates can stand an effective pressure of 60,000 pounds per square inch, or three times the pressure at the greatest ocean depth. The magnet was designed by D. Bruce Montgomery of the laboratory staff.

different charge or momentum, and in particle accelerators to confine the particles to circular orbits.

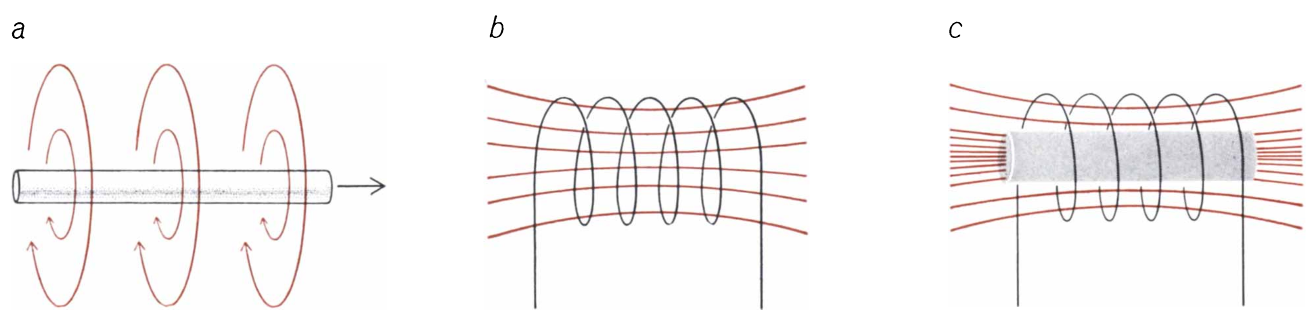
All these examples involve the use of a magnetic field to manipulate charged particles moving more or less coherently in a beam. There are two noteworthy applications that involve the incoherent motion of electric charges. One of these is the confinement of plasmas, or highly ionized gases, at very high temperatures by a suitably shaped magnetic field of sufficient intensity [*see upper illustration on page 71*]. Theoretically such a "magnetic bottle" should be capable of confining the plasma particles without energy losses, so that they could be heated to the enormously high temperatures required to achieve thermonuclear fusion; any material container would absorb so much thermal energy from the plasma that it would vaporize instantly.

A magnetic field can also be employed to manipulate randomly moving charged particles inside a conducting solid. The applied magnetic field will force the particles to move in open circular orbits much like the particles in a cyclotron. All the particles will of course continue to move at random velocities and in random directions. By a lucky chance, however, particles that have the same charge-to-mass ratio will orbit at the same frequency, the faster ones executing larger orbits than the slower ones. Even though the velocities and directions of the particles remain random, then, their motions have a certain harmony. The effect of this harmonious motion, provided that collisions are not so frequent as to disrupt the harmony, is observable as a macroscopic resonance at a characteristic "cyclotron frequency." Thus a magnetic field can give rise to resonance even in nonmagnetic substances, as long as they do not contain so many charge carriers that the collision time is shorter than the orbiting time. In some substances—for example semiconductors "doped" with impurities—intense magnetic fields are required to make the orbiting time very short and the corresponding cyclotron-resonance frequency very high. Most of our knowledge about the charge carriers in semiconductors has been obtained by such cyclotron-resonance measurements at microwave frequencies. More recently the availability of intense magnetic fields has extended the technique to metals at infrared frequencies.

The third effect of a magnetic field—the force exerted on a magnetic dipole by a field diverging in space—is responsible for the attraction and repulsion of two bar magnets or two pieces of lode-



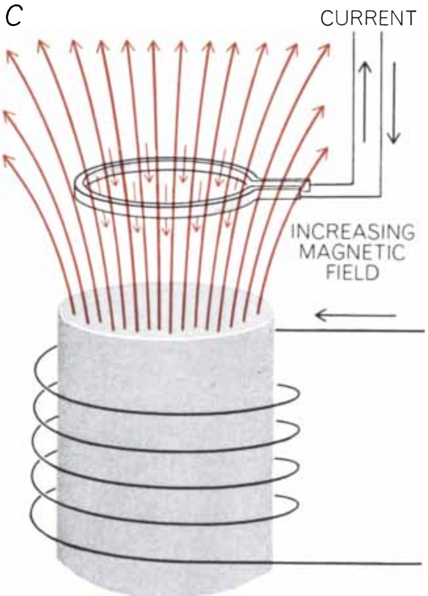
FOUR BASIC EFFECTS of a magnetic field are represented here by examples. In *a* a homogeneous, stationary magnetic field exerts a torque, or twisting force, on two magnetic dipoles: a compass needle and an atomic dipole. The atomic dipole precesses, or wobbles, around a magnetic-field line at a characteristic frequency. The homogeneous, stationary field in *a* also exerts a deflecting force on moving electric charges: two electrons are shown executing different circular orbits in the same period of time. In *b* a diverging field exerts a force on a beam of magnetic dipoles: the beam is split into two separate beams having opposite magnetic-dipole



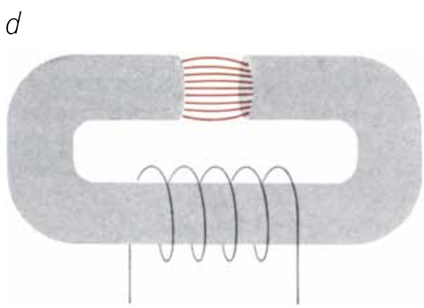
MAGNETIC FIELDS CAN BE GENERATED in the laboratory by the four techniques depicted here. The simplest technique is to pass an electric current through a wire (*a*). By winding the wire into a solenoid, or helical coil (*b*), the lines of magnetic force can be gathered into a more intense "bundle." An iron rod placed in the same coil (*c*) will increase the intensity a thousandfold, because the atomic dipoles in the iron will be aligned by the field of the coil. In a permanent magnet some of this alignment remains after stone. It is this effect, of course, that first attracted man's attention to the phenomenon of magnetism. The principal application of the effect in modern research is to distinguish between nuclei, atoms or molecules that differ in their magnetic-dipole moment. If a beam of atoms, say, is passed through a diverging magnetic field, atoms that have a larger magnetic-dipole moment will be deflected more than those having a smaller one. Indeed, we owe much of our knowledge about the behavior of atoms and molecules and their constituents to this effect, including the revolutionary discoveries that the electron spins about its axis and that the neutron, which possesses no electric charge, nevertheless has a magnetic-dipole moment.

The fourth and last effect of a magnetic field—the force exerted on a stationary electric charge by a field that varies in time—is simply the phenomenon of electromagnetic induction, discovered by Michael Faraday in 1831. In addition to being the backbone of the entire electric power industry, it is precisely this interaction of a fluctuating magnetic field with an electric charge that makes possible the propagation of energy in the form of electromagnetic radiation; among its almost countless other benefits, it is responsible for keeping our planet warm.

A magnetic field that varies in time causes any electric charge in the vicinity to flow in such a direction as to oppose the change in the magnetic field. The opposing flow of charge is called an eddy current, and it acquires a tremendous intensity when the magnetic field changes suddenly. Eddy currents can prevent pulsed magnetic fields from penetrating metals, an effect that has been exploited to concentrate pulsed fields. The effect has also been used to "cold-form" metals by allowing the eddy current to force the metal into a single die, thereby avoiding the need for a mating set of dies [*see lower illustration on page 71*]. Another promising application of eddy currents is the heating of plasmas by magnetic compression to achieve controlled thermonuclear fusion. Thus intense magnetic fields are involved in producing the highest as well as the lowest attainable temperatures.



moments. In *c* an increasing field exerts a force on stationary electric charges: the charges flow in such a direction as to oppose the change in the magnetic field. The induced current is called an eddy current.



the coil is removed. The iron rod can be topologically deformed (*d*) so as to funnel the lines of magnetic force through an air gap, as in the electromagnet on page 72.

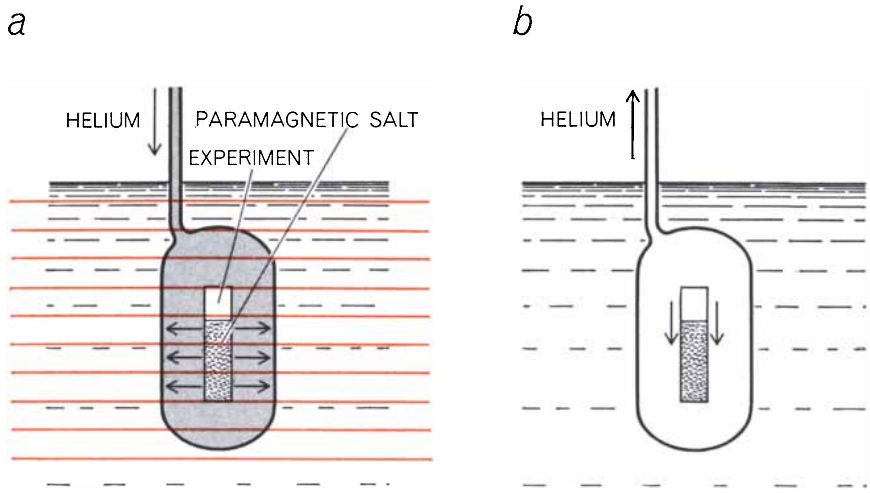
This, then, is a complete picture, in terms of classical physics, of how a magnetic field manifests itself, together with examples of the contributions its four basic manifestations have made to knowledge. Before discussing some of the important submicroscopic implications of these effects in terms of quantum mechanics we shall consider how magnetic fields arise, both in nature and in the laboratory.

The Origin of Magnetic Fields

As we have mentioned, all observed magnetic fields are dipolar, which is the same as saying that their lines of force form closed loops. It is therefore possible to attribute all observed magnetic fields to the circulation of electric charges, although in many cases the existence of the electric charge has been postulated rather than observed. A notable example of this is the neutron; another is the earth, whose magnetic field must be explained by a rather elaborate hypothesis involving self-generating currents that have never been observed directly. The earth's magnetic field, by the way, amounts to about half a gauss. It therefore occupies an intermediate position between galactic fields, which extend over vast distances but amount to only a few thousandths of a gauss, and fields in the vicinity of atomic nuclei, which occupy tiny volumes of space but may exceed a million gauss. Magnetic fields generated in the laboratory have surpassed atomic fields in both intensity and volume.

Certain substances—for example iron, cobalt and nickel—exhibit a property known as ferromagnetism: their atomic dipoles interact strongly enough to become aligned over macroscopic regions, called magnetic domains. When an external field is applied, the domains are themselves aligned, producing a cumulative magnetization that may be several thousand times more intense than the applied magnetic field. Substances are said to be magnetically "hard" if the magnetization remains after the external field is removed; otherwise they are magnetically "soft." The magnetic-field intensity obtainable from lodestone and other naturally magnetized ore amounts to several hundred gauss, and permanent magnets made of modern alloys will produce as much as 10,000 gauss. Electromagnets, iron magnets that are kept magnetized by a surrounding electric coil, can be readily made to generate fields as high as 30,000 gauss. At this point all the atomic dipoles are completely aligned, and forcing more electric current through the coil will not produce any further increase in the magnetization of the iron; the iron is said to be magnetically saturated.

It is possible in principle to generate infinitely strong fields by surrounding an air gap with saturated iron magnetized in suitably diverging directions [*see illustration on page 73*]. The contribution from each additional atomic dipole will decrease as the cube of its distance from the air gap, but as it happens the space available to be filled with iron increases exactly as the cube of its distance from the air gap. Several giant electromagnets were actually made about the time of the first World War; one was a 110-ton magnet, built at Bellevue in France, that achieved 70,000 gauss. As one might expect, the amounts of iron and electric power required to keep such a magnet magnetized reach staggering proportions, and for all practical purposes 30,000 gauss represents the limit of magnetic-field intensity that can reasonably be generated by magnetizing iron. Fields stronger than 30,000 gauss are more expediently generated inside solenoid



ADIABATIC DEMAGNETIZATION is a technique for attaining very low temperatures with the aid of an applied magnetic field. A vial containing the experiment and some paramagnetic salt is suspended in a vacuum chamber, which is immersed in a bath of liquid helium, kept at 1 degree Kelvin (1 degree centigrade above absolute zero). Helium gas at low pressure is introduced into the vacuum chamber and an intense magnetic field is applied (*a*). The field forces the randomly oscillating atomic dipoles in the salt into partial alignment, releasing energy in the form of heat. After cooling the salt back to 1 degree Kelvin, the vial is isolated from the helium bath by evacuating the chamber, and the magnetic field is turned off (*b*). The dipoles resume their random orientations, extracting energy from other types of thermal motion. In this way the salt can be cooled to small fractions of a degree Kelvin; the stronger the applied field, the lower the final temperature.

(coil) magnets without the aid of iron. It is the difficulty of doing without iron that has established a logical boundary between "ordinary" and "intense" magnetic fields and has delayed progress beyond the saturation limit of iron until quite recently.

The difficulty of generating intense fields is twofold and is related to the enormous current densities required to make up for the lack of iron. Although a magnetic field contains stored energy, much like a compressed spring, it should in principle require no continuous expenditure of energy to maintain it; any permanent magnet testifies to this fact. Nevertheless, generating intense magnetic fields is the only process customarily performed at zero efficiency: all of the energy dissipated in a magnet coil must be removed as heat, and removing the energy as heat is considerably more difficult than introducing it as electric power. Hence the first problem of generating intense magnetic fields is the problem of cooling the magnet's coils.

The second source of difficulty is related to the mechanical force exerted by a magnetic field on the electric current that contains it; this force is the magnetic equivalent of pressure. At 250,000 gauss the pressure reaches the yield strength of copper, with the result that an ordinary copper coil, no matter how well it is supported from the outside, will begin to flow like a liquid. At a million gauss the energy density of a magnetic field is equal to the energy density of TNT, and the problem of containing a million-gauss field is comparable to the problem of containing a chemical explosion. The solution of both problems calls for a massive structure, but in the case of the magnetic field the structure must also be able to carry huge electric currents and be perforated with enough cooling channels to remove the enormous heat generated by the currents. For practical purposes the structure cannot be made of any material stronger than copper, because all the stronger materials have much higher electrical resistance and therefore produce so much more heat for the same electric current that the required increase in the number of cooling channels would much more than offset the increase in strength obtained.

As a given solenoid magnet is driven to stronger and stronger fields, the amount of power required increases as the square of the field intensity, and the magnetic pressure increases accordingly. Above 250,000 gauss it becomes necessary to use increasingly massive coils, in which the current is distributed over larger and larger volumes in order to reduce to a tolerable level the magnetic pressure near the center of the coil. The inefficient current distribution that inevitably results causes the power requirement for electromagnets stronger than 250,000 gauss to increase even more drastically than the square of field intensity. The steeply increasing power requirement in turn further increases the cooling requirement; not far beyond the 250,000-gauss point the power requirement becomes absurd even by "space age" standards. The practical range of "intense," continuous magnetic fields is confined between the magnetic failure of iron at 30,000 gauss and the mechanical failure of copper at 250,000 gauss.

Superconducting Magnets

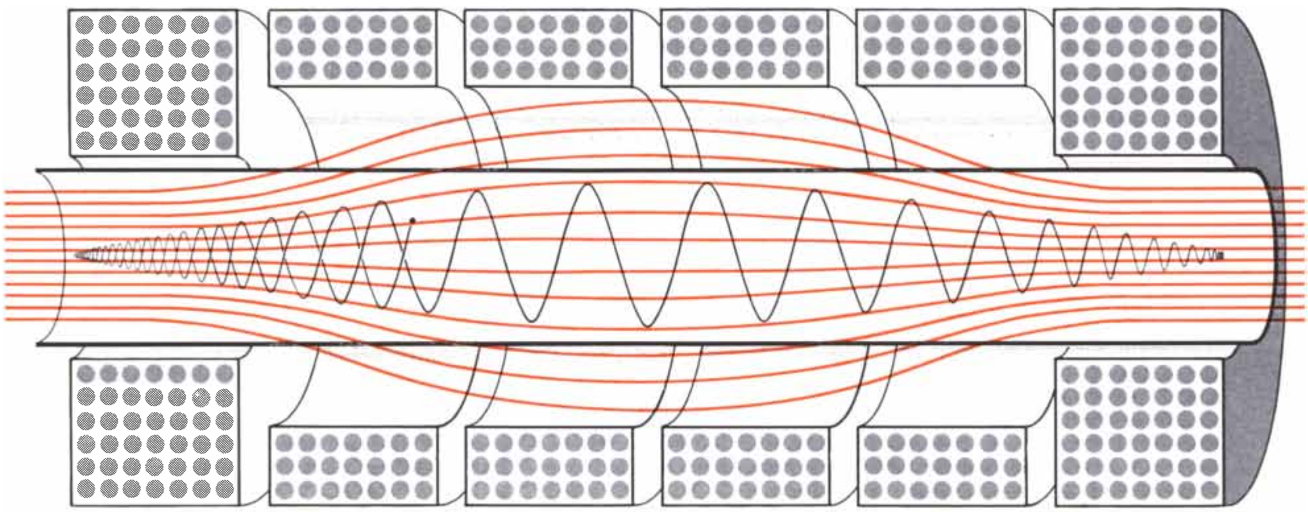
There are two shortcuts around the twin problems of power and cooling in the generation of intense magnetic fields; one involves the use of superconducting materials in the construction of the magnet and the other involves pulsed fields. It has been known since 1911 that certain substances exhibit no resistance to the flow of an electric current at temperatures near absolute zero. This potentially useful property has always been observed to vanish, however, with the application of even a moderately strong magnetic field. Then in 1960 it was discovered that certain metallic alloys, such as niobium-tin, remain superconducting in intense magnetic fields [see "Superconducting Magnets," by J. E. Kunzler and Morris Tanenbaum; Scientific American, June, 1962]. New superconducting alloys have since been perfected that permit the generation, without losses due to electrical resistance, of magnetic fields as high as 100,000 gauss. Beyond this point the current-carrying capacity of the best-known alloys falls off so sharply that the technique is not likely to be pushed beyond about 170,000 gauss in the foreseeable future.

Superconducting magnets have served the useful purpose of making the lower range of intense magnetic fields generally available at a reasonable cost. Ultimately such magnets will contribute to the higher range by replacing the outermost windings of copper magnets; these windings do not contribute a great deal to the full inner field, but as a result of their size they consume much of the electric power required by the entire magnet. At present the superconducting alloys required for this purpose still cost as much as the electric generators they would replace. Nevertheless, superconducting magnets are so promising for some applications that they are being actively developed in spite of the present high cost of the alloys. For example, the confinement of plasma in a thermonuclear reactor and the direct conversion of heat into electric power by a magnetohydrodynamic generator both require moderately intense magnetic fields in large volumes.

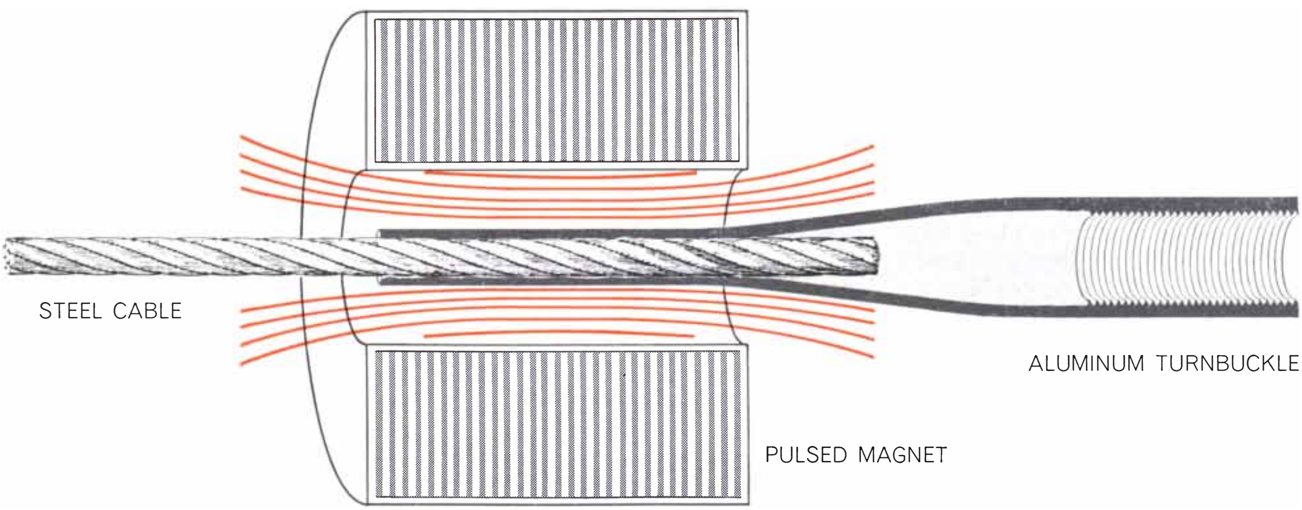
Potential space applications of superconducting magnets include the inductive storage of electric energy in superconducting coils (to replace batteries) and the shielding of space travelers by the magnetic deflection of high-energy charged particles (to replace heavy shielding). Inertial-guidance navigation systems may ultimately make use of magnetically supported, frictionless gyroscopes employing currents in a superconductor. The loss-free generation, transformation and transmission of electric power by superconductors may someday revolutionize the entire power industry. The feasibility of all these applications depends heavily on having intense magnetic fields available to carry out the necessary research. Thus the exploitation of superconductivity has increased rather than decreased the need for normally conducting magnets capable of generating intense magnetic fields.

Pulsed Magnets

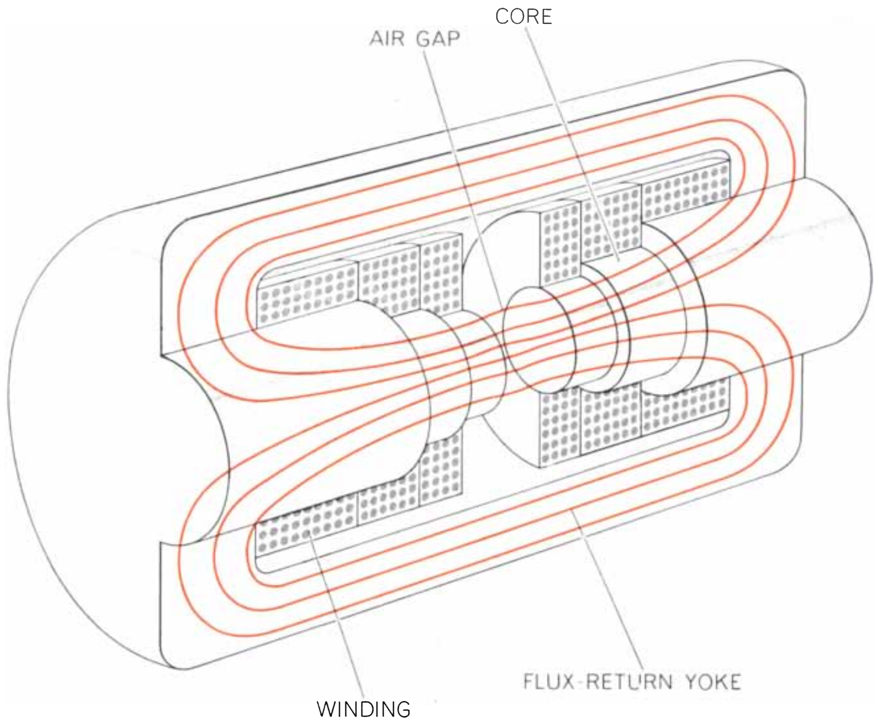
The second shortcut around the problems of power and cooling in large magnets is to generate fields in such short pulses that the cooling problems can be ignored. Thermal inertia keeps the coil from vaporizing and mechanical inertia helps to hold it together against the explosive magnetic forces. As early as 1924 the Soviet physicist Peter L. Kapitza, then working at the University of Cambridge, succeeded in generating fields as high as 500,000 gauss for several thousandths of a second. He did this by short-circuiting a large alternating-current generator across a small, jelly-roll-shaped coil for a single half-cycle of current. Kapitza was able to perform many physical measurements during this short pulse. His optical-beam galvanometers were set up far enough



"MAGNETIC BOTTLE" is designed to confine plasmas, or highly ionized gases, at very high temperatures by a suitably shaped magnetic field of sufficient intensity. Such a device should be capable of confining the plasma particles without loss so that they can be heated to the enormously high temperatures required to achieve thermonuclear fusion; any material container would vaporize instantly at such temperatures. A single plasma particle is shown being "reflected" from end of coil, where the field is more intense.



METALS CAN BE "COLD-FORMED" by a process based on the formation of eddy currents in a metal as a result of rapid changes in the intensity of the surrounding magnetic field. The eddy current prevents a pulsed field from penetrating the aluminum turnbuckle, causing it to be compressed around the irregular cable far more accurately than would be possible using a mechanical die.



ELECTROMAGNET, or an iron magnet that is kept magnetized by electric coils, can be readily made to generate fields as high as 30,000 gauss. At this point all the atomic dipoles are completely aligned and the iron is said to be magnetically saturated. Fields stronger than 30,000 gauss are more expediently generated inside coil magnets without iron.

away from the generator so that they could record the outcome of his experiments on free-falling photographic plates before the ground tremor caused by the explosive short-circuiting reached them. All the ingenuity in the world, however, could not make up for the lack of time. Some experiments simply require more time and Kapitza's apparatus could not provide it.

Although pulsed fields will never eliminate the need for continuous intense fields, they have recently been pushed to new levels of intensity. The first advance since Kapitza came in 1956, when Simon Foner and one of us (Kolm) generated pulsed fields of 750,000 gauss at the Lincoln Laboratory of M.I.T. by discharging a bank of capacitors into a helix made of beryllium-copper, an alloy with greater strength but also much higher electrical resistivity than pure copper. By rapidly transferring the energy from the capacitor bank into the magnetic field and back again into the capacitors under resonant conditions, resistive heating was made unimportant. These pulses lasted only 120 millionths of a second, but our instruments were able to record for the first time cyclotron resonance in a semimetal (bismuth) at infrared frequencies. The same technique was later pushed to a million gauss, but the coils barely survived at this intensity.

We soon found that it was more expedient to rely on an effect mentioned earlier, namely the fact that self-induced eddy currents can prevent a rapidly increasing magnetic field from penetrating a metal. This effect has led to three methods for confining pulsed magnetic-flux lines into a smaller cross-sectional area than they would normally occupy, thereby increasing the intensity of the field. Flux lines can be forced to pass through a slotted metal funnel inside a pulsed-field coil, the funnel being stronger and more massive than the coil. Flux lines can also be compressed by forcing a liquid metal to flow radially inward in a cylindrical space surrounded by magnetic coils. Finally, flux lines can be compressed by collapsing a metal container around them by means of an explosive charge. Using this "implosion" method, C. M. Fowler of the Los Alamos Scientific Laboratory has generated fields as high as 15 million gauss for two millionths of a second. With improved instruments it may soon be possible to perform useful experiments under these conditions.

Since 1924 pulsed-field techniques have successfully explored a wide range of phenomena. Many experiments, however, are not accessible to these techniques, including the achievement of very low temperatures by adiabatic demagnetization and the observation of atomic spectra in intense magnetic fields. The application of a magnetic field to radiating atoms causes certain of their spectral lines to split into two or more lines, an effect named after its discoverer, the Dutch physicist Pieter Zeeman. As the new quantum mechanics began to explain atomic spectra, it became increasingly important to follow Zeeman splitting to more intense magnetic fields. Since hours of exposure time are required to record faint spectral lines, it was also necessary to maintain the intense fields continuously and with good accuracy.

The Bitter Magnet

This challenge was met in 1936 by Francis Bitter of M.I.T. with the development of a solenoid magnet capable of generating a continuous field of 100,000 gauss in a one-inch bore. Bitter's magnet was about the size of an automobile wheel; it consisted of copper disks slotted along a radius and interleaved with mica disks in such a way as to form a conducting copper helix [*see upper illustration on page 74*]. The entire stack of plates was perforated by almost 600 small holes, each with a diameter of an eighth of an inch, through which cooling water was pumped in the axial direction. The solenoid was supplied with a total power of 1.7 million watts and was cooled by 800 gallons of water per minute. As in all high-performance magnets, direct contact between the water and the copper was necessary, since any intervening insulation would provide a barrier to heat transfer. Electrolytic conduction through the water was negligible compared with the total power consumption.

Bitter's original magnet installation remained in continuous operation from its completion in 1936 until 1962, with a brief interruption during World War II, when the generators were lent to the Manhattan project for the separation of uranium isotopes at Oak Ridge. In 1947 a duplicate magnet facility was built at the Naval Research Laboratory in Washington to accommodate the backlog of experiments waiting for time on the original magnet. Several similar facilities have since been built in various laboratories throughout the world. All the latter projects, however, were aimed at providing moderately intense continuous fields and were not designed to advance the art of generating more intense fields. The original Bitter solenoid remained the most intense, continuous-field magnet in the world from 1936 to 1958, when interest in generating more intense fields was revived at M.I.T.

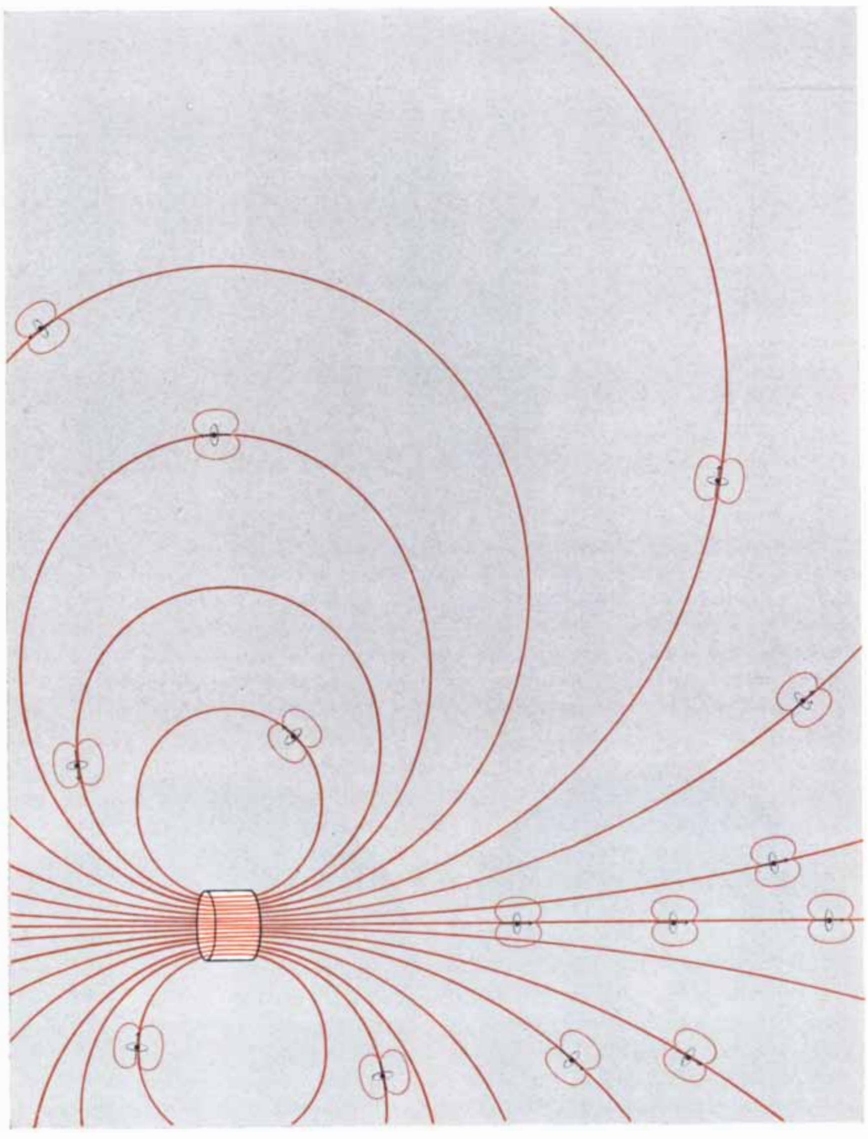
The decisive impetus for the present emphasis on very intense continuous fields came from Benjamin Lax and his group of solid-state researchers at the Lincoln Laboratory. This group had been struggling for years with the frustrating problem of making resonance measurements with pulsed fields. Now Lax and his associates joined forces with Bitter to investigate the possibility of pushing new substances and designs toward levels of heat transfer more than 10 times higher than those that had been considered daring in 1936. Surprisingly some of the test structures were found to dissipate more heat per unit of cooling surface than is dissipated by the surface of the sun! Out of this renewed activity came new methods of field-control and data-acquisition, as well as a new family of improved Bitter magnets, which were soon in full use day and night. In 1961 one of us (Kolm) completed the development of a new type of solenoid magnet with a jelly-roll rather than a helical shape [*see illustration on page 76*]. The new magnet, about the size of a grapefruit, was able to advance the maximum field intensity from 100,000 to 126,000 gauss, using the same power plant. Meanwhile at the Naval Research Laboratory more power was made available, and in 1962 it was found that an original Bitter magnet could be made to generate as much as 152,000 gauss.

It soon became obvious that to obtain still stronger continuous magnetic fields a larger and more versatile research facility was needed. The old basement laboratory at M.I.T., cluttered with modern instruments and makeshift power and water connections, had become too crowded for safety, not to mention efficiency or comfort, and the power available was not adequate to push on to more intense fields. The limit of 250,000 gauss using copper now seemed within reach, but it would require roughly a ninefold increase in generator capacity, or some 15 million watts. An installation of this size was justified only if it could be effectively used by many researchers; this required flexibility in design, a large amount of space and many supporting facilities. After much planning a proposal was prepared for review by various committees representing the scientific community at large. Two years later Department of Defense approval was obtained and support was provided by the Air Force. The new National Magnet Laboratory began operating in the fall of 1963.

The National Magnet Laboratory

The new laboratory is housed in a completely remodeled former bakery building located at the edge of the M.I.T. campus. The power plant consists of two identical motor-generator units, each composed of a 600-horsepower starting motor, a 6,000-horsepower driving motor, an 82-ton steel flywheel and two direct-current generators. Each generator is capable of continuously supplying 10,000 amperes of current at 250 volts, or the equivalent of 2.5 million watts. For short periods of time they can generate up to four times as much overload. The plant thus has a total continuous capacity of 10 million watts, a five-minute overload capacity of 16 million watts and a two-second overload capacity of 32 million watts (using the energy stored in the flywheels). There are 10 separate experimental cells, or magnet laboratories, and the four generators can be operated independently to supply 2.5 million watts to any four of the cells simultaneously; they can also be connected in series, in parallel or in any series-parallel combination to supply all of their power to a single cell.

A closed-loop cooling system is capa-

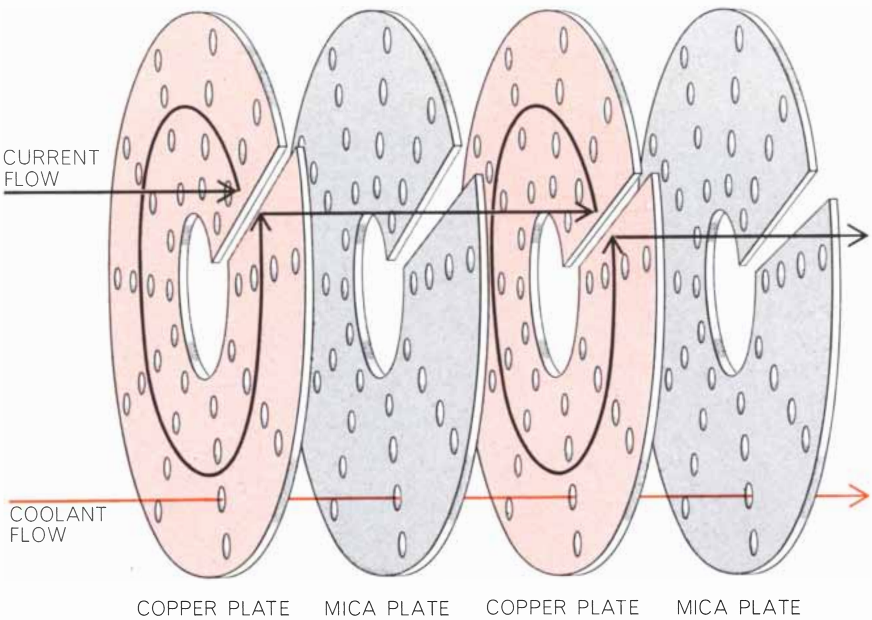


INFINITELY STRONG MAGNETIC FIELD can be generated in theory by surrounding an air gap with a universe of magnetically saturated iron, magnetized in suitably diverging directions. As successive layers of iron are added, the field contributed by each dipole falls off as the cube of its distance from the air gap, but as it happens the space available to be filled with iron increases exactly as the cube of its distance from the air gap.

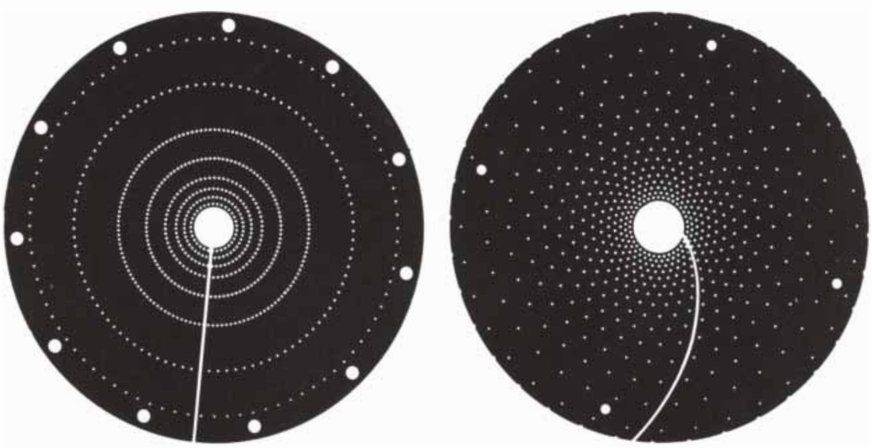
ble of circulating 4,000 gallons of deionized and deoxygenated water through any combination of magnets and transferring the total power capacity of the generators as heat to water from the Charles River through a series of heat exchangers. All switches and valves are operated from a central control room, so that power and water can be transferred instantly from one cell to another without interrupting any of the experiments in progress. The demand for intense-field experiments has already become so great that the laboratory now provides full power for 16 hours a day.

Time-sharing is working out so effectively that the four generators are capable of supplying power to more than the 10 existing cells; additional cells are being planned.

The laboratory has a growing family of solenoid magnets, now numbering about 16, which can accommodate experiments at any temperature currently attainable. These range from a variety of modernized Bitter magnets, designed to generate about 100,000 gauss with the aid of a single generator, to a giant three-stage solenoid capable of generating slightly more than 250,000 gauss using all four generators [*see illustrations on page 67*]. The goal of a 250,000-gauss continuous magnetic field was achieved last year, a year and a half after the opening of the laboratory.



BITTER SOLENOID, invented by Francis Bitter of the Massachusetts Institute of Technology in 1936, is the prototype of many of the modern intense-field magnets, including the 250,000-gauss magnet. Slotted copper disks separated by insulating mica disks were compressed in such a way as to form a continuous conducting helix (*black arrows in this exploded view*). The entire stack was perforated by more than 600 small holes through which cooling water was pumped at a rate of 800 gallons per minute. Magnet consumed more than two million watts of power and generated a field of slightly more than 100,000 gauss.



ARRANGEMENT OF COOLING HOLES in the solenoid plates of the original Bitter magnet (*left*) and a modern magnet descended from it (*right*) are compared in this illustration. The modern arrangement ensures a more even distribution of coolant in the magnet.

The 250,000-Gauss Magnet

Designed by D. Bruce Montgomery, this magnet consists of three coaxial solenoids having an inside diameter of slightly over two inches and an outside diameter of 36 inches. At full power it consumes 16 million watts and 2,000 gallons of water per minute. The outermost section is a massive winding of hollow, square copper conductors, which use a quarter of the total power and generate 50,000 gauss in a 14-inch bore. This section surrounds two inner sections, which are helical and are made of compressed stacks of slotted copper disks provided with chemically etched cooling channels extending radially like the spokes of a wheel. Cooling water is forced through these channels by an elaborate manifold system.

The innermost helix has an outside diameter of six inches and is supplied with only as much power as mechanical forces will allow, which amounts to another quarter of the total. The intermediate solenoid consumes the remainder, or half of the total power. The entire magnet contains three tons of copper, and the innermost plates can withstand an effective pressure of 60,000 pounds per square inch, or three times the pressure at the greatest ocean depth.

Some of the solenoid magnets at the laboratory are designed for special purposes, such as optical experiments requiring access to the magnetic field in the lateral as well as in the axial direction. One solenoid provides a magnetic field that is homogeneous to within one part in a million over a relatively large volume, and is stable in time to half a part in a million, in order to achieve good resolution in nuclear-magnetic-resonance experiments; another generates a field that is deliberately inhomogeneous to serve as a magnetic bottle for confining plasma particles.

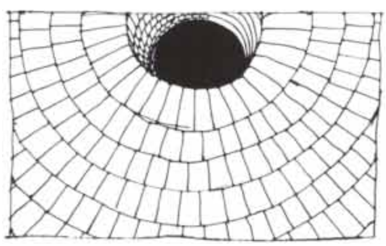
New magnets combining the advantages of water-cooled solenoids and superconductors are under development. The most advanced solenoid will probably not be completed for some time. It is expected to generate 400,000 gauss for a period of two seconds by using the full overload capacity of the generators, as well as the energy stored in the flywheels. It will be cooled by a surge of water driven by the accumula-

NASA'S furnace simulates space re-entry conditions... crucial test for A. P. Green's super refractories

At National Aeronautics and Space Administration's Ames Research Center in California, they test models of various types of re-entry vehicles, such as the Apollo and M-2 lifting entry body. Testing is in a large hypersonic wind tunnel under high heat conditions that simulate portions of the re-entry corridor into the earth's atmosphere.

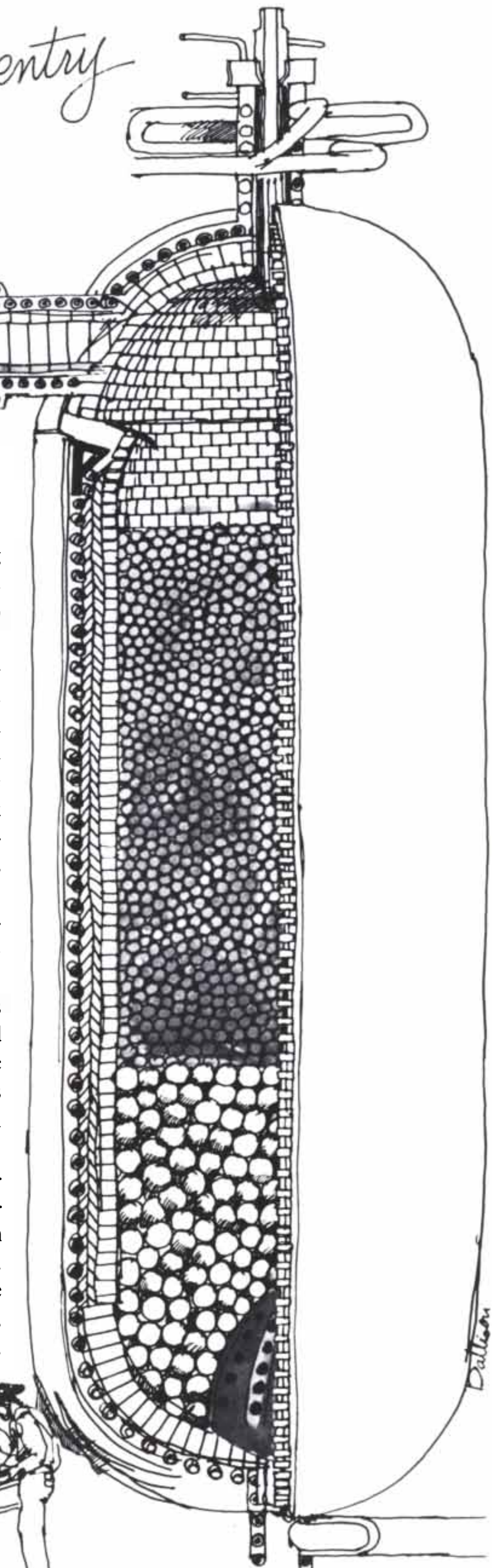
Heat comes from a unique pebble-heating furnace. Perhaps the largest of its type, the 35-ft furnace is lined with super high-alumina refractories made by A. P. Green Fire Brick Company. They replaced an earlier, much more expensive oxide material that did not perform satisfactorily.

In operation, ambient air is introduced through the preheated pebble bed until the desired pressure is reached, then discharged into the wind tunnel. Inner lining of the furnace is A. P. Green's 99-AD brick (99 per cent alumina) with back-up insulation of its CRYSTALITE L (72 per cent alumina). The pebble bed contains 63,000 lb of 1¼-in.-diameter TA 78 (94 per cent Al_2O_3) pebbles at the bottom. Above these are some 105,000 lb of X99A (99 per cent Al_2O_3) 1-in. pebbles. The installation is designed for temperatures in excess of 3,000°F.



Modern, high-alumina refractories demonstrate remarkable service life and versatility. Made with Alcoa® Aluminas, A. P. Green's super refractory products are used widely today in the glass, ceramic and steel industries; in nonferrous foundries and in numerous special applications.

Alcoa does not make refractories, but we do supply the high-grade aluminas that make modern refractory performance possible. For more information, please write Aluminum Company of America, 814-D Alcoa Building, Pittsburgh, Pennsylvania 15219.



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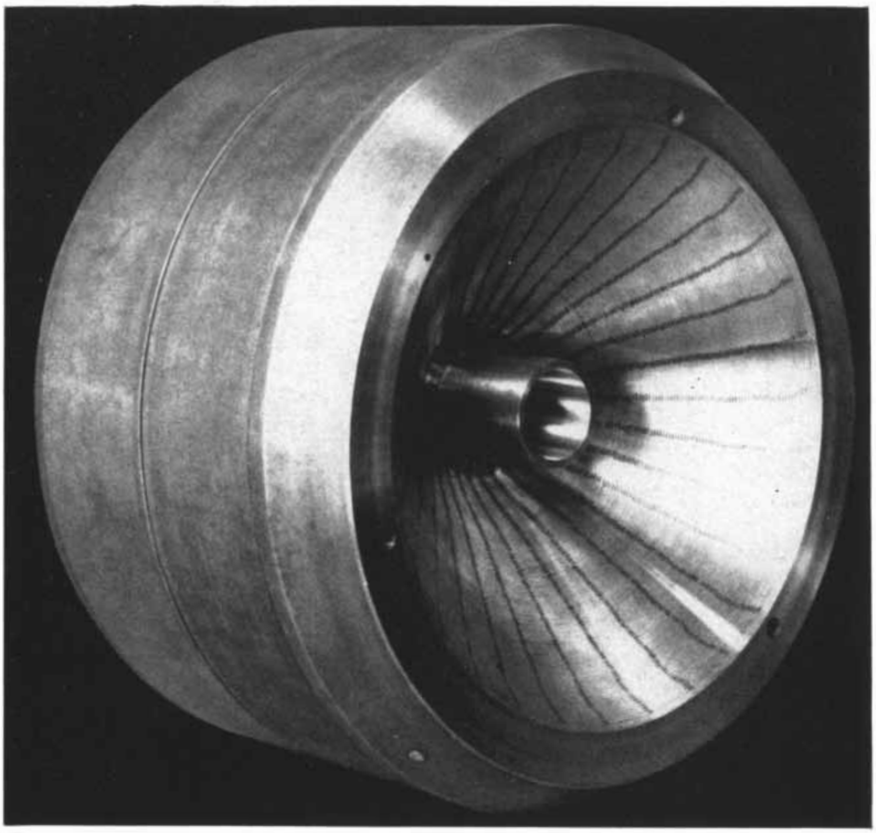


KOLM SOLENOID, invented in 1961 by one of the authors, is shaped like a jelly roll rather than a helix. A strip of copper 140 feet long and six inches wide is rolled around a tube one inch in diameter. Cooling channels are machined into strip in such a way that they line up like the spokes of a wheel (*dark radial bands*). After the copper strip is completely rolled up the resulting cylinder is machined out at the ends to form funnel shapes, which improve the current distribution. The magnet is capable of generating 126,000 gauss.

tor tanks of a surplus aircraft-launching catapult.

Not all of the research is done in high-power solenoid magnets. The laboratory also has a number of conventional iron electromagnets, a sizable pulsed-field installation and several superconducting magnets. It is the function of the laboratory not only to supply intense or specialized magnetic fields for research but also to serve as a center for advancing the art of generating magnetic fields. Previously magnets had always been designed rather casually as a means to an end by physicists whose main interest lay elsewhere. Now for the first time the art is being pursued by a specialized engineering staff under the direction of Montgomery.

Scientific research at the laboratory is carried out by a permanent staff of theoretical and experimental physicists headed by Lax, director of the laboratory since its inception, and one of us (Freeman), the associate director. About half of the research in intense fields is done by a steady procession of visiting workers from academic, Government and industrial laboratories, working either independently or in collaboration with the permanent staff. Many of the phenomena that are being studied are observable only in intense fields.

The Future of Intense-Field Research

One of the most significant scientific advances of our age has been the discovery of macroscopic quantum states, or systems of electrons that in macroscopic dimensions exhibit the properties of waves that are coherent, or all in step. Since intense magnetic fields are capable of selectively influencing the basic constituents of matter and the quantum laws that govern their interaction, such fields have already begun to play an important role in studying some of these dramatic macroscopic quantum effects.

A simple example that has already been discussed in purely classical terms is cooling by adiabatic demagnetization. The application of a magnetic field to a magnetic atom creates a previously nonexistent distinction between different orientations in space: the atom will tend to align with the field because energy is required to disalign it. In the language of quantum mechanics, the magnetic field has split two "states" that previously were "degenerate" (that is, had the same energy); the "antiparallel" state now becomes a state of higher energy than the "parallel" state. The difference in energy between the two states depends on the magnitude of the atom's magnetic-dipole moment and on the intensity of the magnetic field. If this energy-splitting is large compared with the thermal energy available at the prevailing temperature, then the antiparallel state will become unpopulated; the magnetic field has priced it out of the energy market, so to speak. We have seen earlier how this circumstance leads to a macroscopic effect, namely reversible heating and cooling as the magnetic field is respectively turned on and off. The development of adiabatic-demagnetization devices for various special purposes is being undertaken at the National Magnet Laboratory by Emanuel Maxwell of the permanent staff in collaboration with George Zimmerman of Boston University. The intense magnetic fields now available will extend this old technique to larger working volumes and even lower temperatures.

A striking case of macroscopic coherence is represented by maser and laser action, in which coherent microwave or light radiation is emitted by electrons that exhibit coherent wave properties over macroscopic dimensions. This phenomenon has already begun to revolutionize optics over the entire spectral range. Here again a magnetic field finds a variety of applications, inasmuch as it is capable of varying the energy of quantum levels and hence the frequency of the emitted light, as well as reducing drastically the threshold for the onset of laser action.

For many years superconductors were thought of simply as substances whose electrical resistance vanishes below a certain temperature. This concept met with a number of minor but significant difficulties, which eventually led to the recent realization that superconductivity represents a state of matter in which a large number of electrons are in a coherent state of motion. Such a state can persist indefinitely in flagrant violation of the classical law that a circulating electron must lose energy by radiation. Having accepted the fact that such a macroscopic state can exhibit as much stability as microscopic atomic orbits, it should not have come as a surprise to discover that a supercurrent is quantized in terms of the

magnetic flux it embraces. Robert Meservey of the laboratory staff is currently making use of this effect to study in detail the manner in which a magnetic field penetrates a superconductor.

In order to be useful in the fabrication of superconducting magnets and other applications, a superconducting substance must retain its ability to carry a high current density in the presence of an intense magnetic field. In the case of many new alloys this "critical current density" has been a matter of speculation because of the lack of sufficiently intense fields to permit testing. Montgomery of the laboratory staff and William Sampson of the Brookhaven National Laboratory have just performed the first series of measurements extending to fields intense enough to quench superconductivity in test coils made of some of the best alloys available. These measurements were extended to 205,000 gauss, and indeed an important effect appeared above 178,000 gauss: the product of critical current times applied field, which had remained remarkably constant, began to drop sharply above this point. This circumstance provided a valuable clue concerning the mechanism by which superconductivity begins to break down in complex alloys.

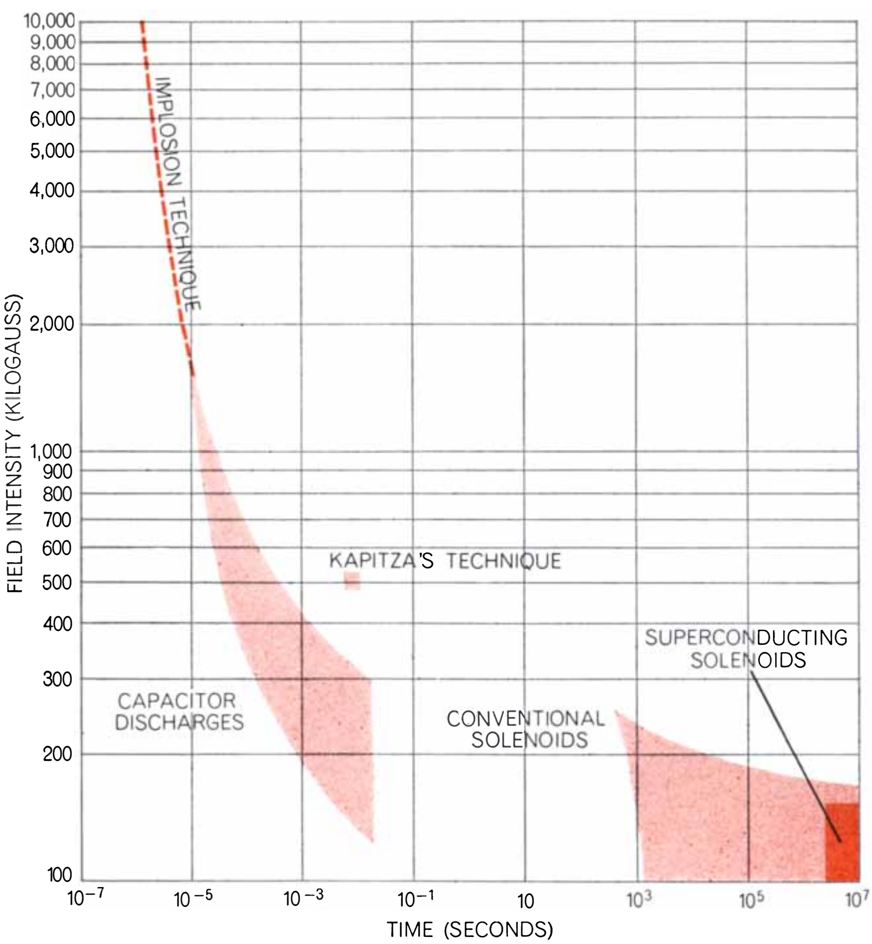
Even conduction in normal materials, once reported by a committee of the Royal Society to be the most unchanging property of matter, has been found to be affected severely by an intense magnetic field. In fact, in Kapitza's first pulsed-field studies he found that deflection of charge carriers by the magnetic field changes the resistance of certain materials by several factors of 10. These magnetoresistance effects are being used by Leo Neuringer at the laboratory to obtain information about the topology of the Fermi surface, the highest energy configuration occupied by electrons in what is called momentum space [see "The Fermi Surface of Metals," by A. R. Mackintosh; SCIENTIFIC AMERICAN, July, 1963].

A number of less common intense-field techniques are being used at the laboratory to explore these Fermi surfaces, from which the most meaningful properties of a material can be predicted. These include the De Haas–Van Alphen effect, magnetoacoustic effects, plasma waves in solids, magneto-optic reflection and absorption, and cyclotron resonance. Continuous fields are essential for all high-resolution applications because they easily provide 1,000 times the resolution of pulsed measurements —the only other means of producing such intense fields.

Intense magnetic fields, now that they are readily available, are finding new applications at a rate that exceeds all expectations. It is difficult to provide anything even approximating a complete picture, and this circumstance in itself indicates how rapidly the techniques of intense-field research are being absorbed into the various major divisions of physics. Some of these applications represent entirely new techniques that were not possible before, as for example an investigation concerning the stability of ball lightning, which has just been started at the National Magnet Laboratory by Paul Silberg of the Raytheon Company.

Other applications represent the extension of known techniques into previously inaccessible ranges of frequency or resolution. For instance, a whole family of experiments related to plasma phenomena in metals is being extended to higher field intensities by Raymond Bowers and his Cornell University graduate students, and independently in semiconductors by Jacek Furdyna of the laboratory staff. The entire family of electron-transport effects, a technique that traces its origin to the use of frog-leg galvanometers in the 18th century, is being pushed to higher fields by Neuringer of the laboratory staff, Ted Harman and J. Honig of the Lincoln Laboratory and K. J. Tauer of the U.S. Army Materials Research Agency. We have already cited examples from the more general field of magneto-optic effects, or "solid-state spectroscopy," as it has come to be called, which is being extended into the high-field region by Lax and his collaborators. Entirely new applications of the Mössbauer effect in exploring solid-state and nuclear phenomena are being undertaken by Norman Blum and one of us (Freeman), both of whom are on the laboratory staff, and Lee Grodzins of M.I.T.

It would require a separate article to do justice to any of these applications, and there can be no doubt that the regular reader of *Scientific American* will encounter many such articles in the years to come.



PRESENT STATE OF THE ART of generating intense magnetic fields is summarized in this graph. Vertical scale indicates intensity; horizontal scale indicates the length of time a particular field can be maintained. Working volumes are not shown in the graph, but generally increase from cubic millimeters at left to tens of cubic centimeters at right.

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*Courtesy of the Lehman collection.

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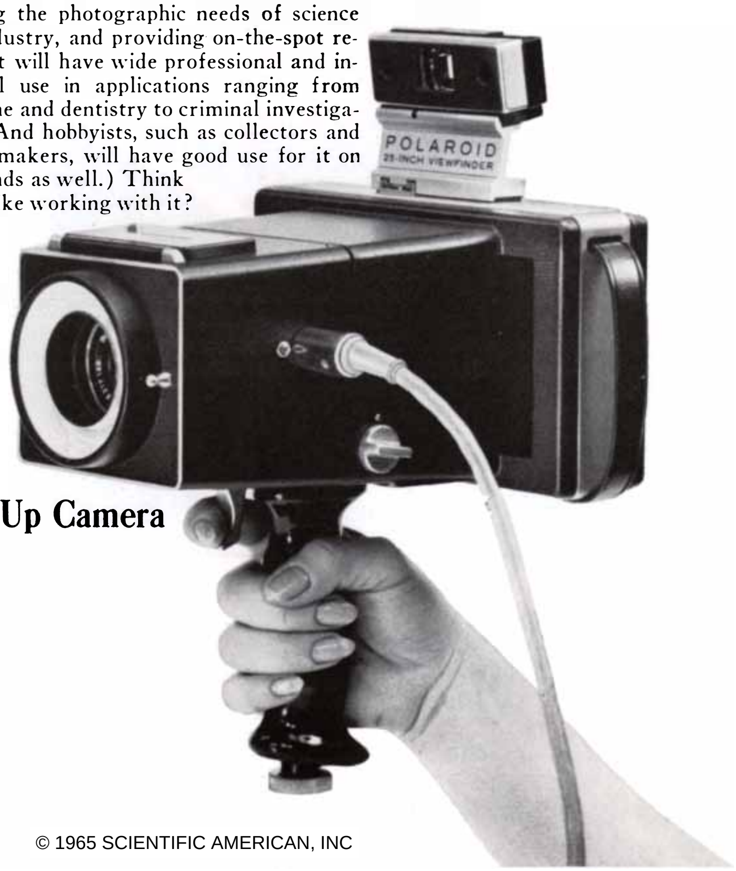

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MACEDONIAN PLAIN in northern Greece is level agricultural land today; 8,000 years ago its central portion was underwater and its coastline was marked by farming communities such as the one found at Nea Nikomedeia, the oldest Neolithic site in Europe.

SCRAPED HALF-ACRE at the Nea Nikomedeia mound shows the pale discolorations that outline the walls of vanished buildings. Several narrow ridges, composed of unexcavated earth, outline the grid of squares into which the site was divided before digging. Near a zigzag in this grid at the right side of the illustration appears the outline of a square structure that was subdivided into one wide and one narrow room; the disturbed outdoor area opposite the narrow room may have been a porch. Just above this house in the photograph, partly obscured by two grid ridges, is the outline of an undivided house like the one illustrated on page 87.

An Early Neolithic Village in Greece

Excavations at Nea Nikomedeia in northern Greece have uncovered a community of 8,000 years ago. Its remains suggest that agriculture and animal husbandry came to Europe earlier than has been supposed

by Robert J. Rodden

The Macedonian plain of northern Greece is covered today with orchards and fields of cotton and sugar beets. The aspect of the plain was quite different 8,000 years ago: its central portion was flooded either by an arm of the Aegean Sea or by a shallow lake. Along the shore lived farmer-herdsmen who raised wheat, barley and lentils, tended sheep and goats and may also have herded cattle and pigs. These facts are known because one of the many low-lying mounds on the Macedonian plain has recently been excavated. Called Nea Nikomedeia after a nearby modern village, the mound marks the site of the oldest dated Neolithic community yet found in Europe.

Perhaps even more important than the antiquity of the site is the fact that the patterns of living it reveals, although they are basically similar to the patterns of village life in early Neolithic sites as far east as Iraq and Iran, have their own exclusively European characteristics. The evidence for the existence of a thriving village in northern Greece near the end of the seventh millennium B.C. makes it necessary to reconsider the accepted view that the agricultural revolution of the Neolithic period was relatively late in reaching Europe from its area of origin in the Middle East. In southeastern Europe, at least, the transition from hunting, fishing and food-gathering in scattered bands to farming, herding and permanent village life must have taken place far earlier than has generally been thought.

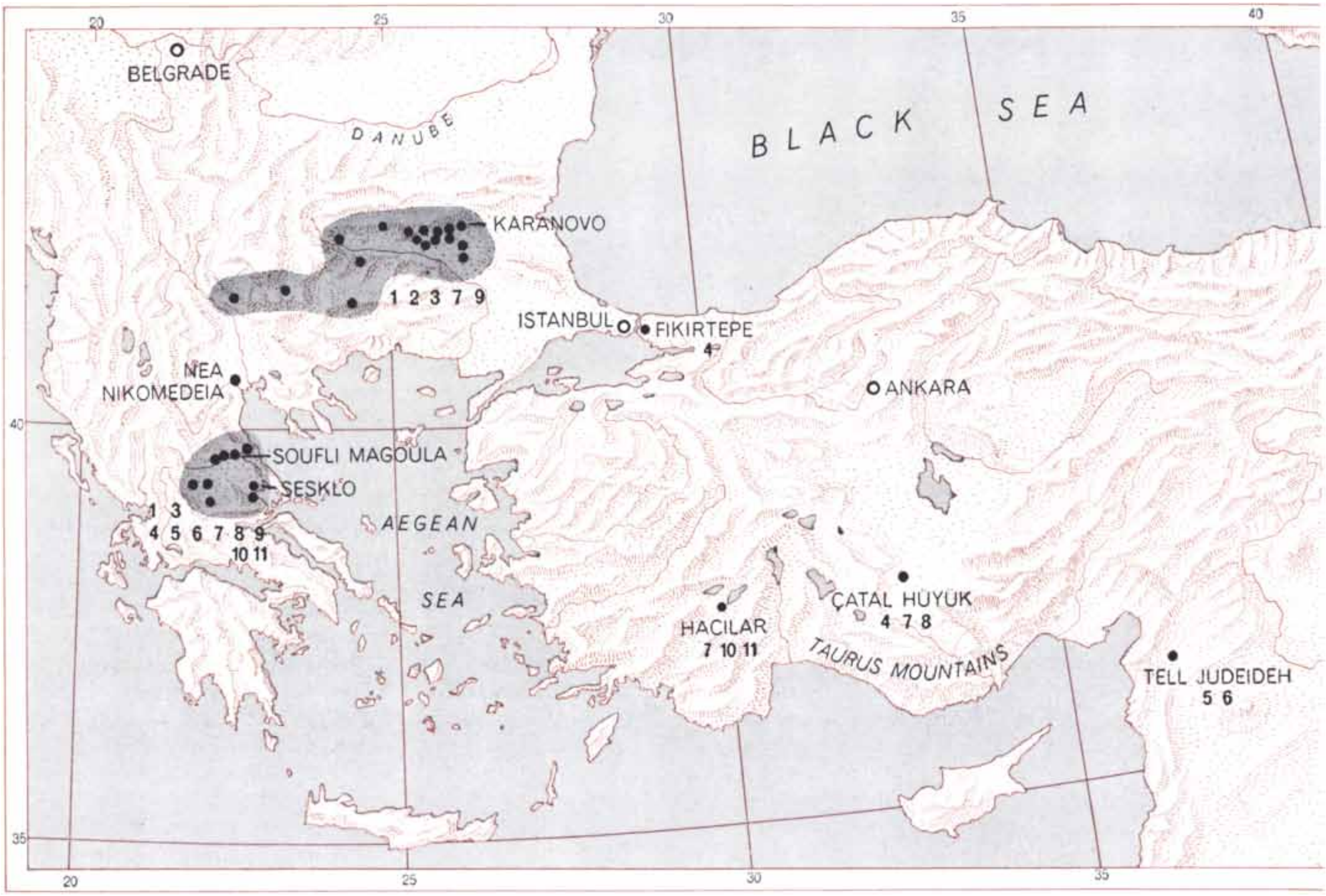
I first made an archaeological reconnaissance of the Macedonian plain with a fellow graduate student, David Clarke, during the fall of 1960. We were seeking evidence that might clarify the relation between what were then the earliest-known farming communities in Europe—most of which are represented by sites in the Danube valley and in eastern Yugoslavia and central Bulgaria—and those early communities in central Greece whose existence had become known to archaeologists as long ago as the 1900's. Lying between the two regions, the Macedonian plain was an obvious place to look for the remains of communities that might have had connections with the first agriculturists to the north and south.

The Nea Nikomedeia mound had come to the attention of Photios Petsas of the Greek Archaeological Service in 1958, when local road builders bulldozed away three-quarters of an acre of it to use as highway fill. Petsas put a stop to this and, when we consulted him in 1960, directed us to the site. On the bulldozed surface, level with the surrounding plain, we found fragments of pottery and other artifacts that closely resembled the finds from the lowest excavated levels at Neolithic sites in central Greece.

A six-week campaign of exploratory excavation was mounted during the summer of 1961 under the direction of Grahame Clark of the University of Cambridge and myself. The work was done under the auspices of the British School of Archaeology in Athens and in cooperation with the Greek Archaeological Service; the necessary funds were provided by the Crowther-Benyon Fund of the University of Cambridge (which had sponsored my 1960 reconnaissance), the British Academy and the Wenner-Gren Foundation for Anthropological Research. Excavation quickly demonstrated that there was a rich layer of early Neolithic material at Nea Nikomedeia; pottery and other artifacts from this layer showed affinities with material from the earliest pottery-using Neolithic settlements in central Greece and, as we had hoped, with artifacts from the first well-established farming communities to the north.

Impressions of cereal grains, preserved on pottery surfaces, and more than 400 fragments of animal bones demonstrated that the first settlers at Nea Nikomedeia practiced an economy of mixed farming and herding. The 1961 excavations also established the fact that the first houses at the site were rectangular structures with mud walls supported by a framework of wooden poles. Samples of organic material from the site were sent for analysis to the Radiocarbon Dating Laboratory at the University of Cambridge; the analysis yielded a figure of 6220 B.C. ± 150 years. This is the earliest date as yet assigned to Neolithic material from Europe.

It was not until the summer of 1963 that a full-scale excavation could be organized at Nea Nikomedeia. In that year much of the early Neolithic occupation level was uncovered as part of a joint Harvard-Cambridge field project sponsored by the National Science Foundation. As before, the work was done under the auspices of the British School of Archaeology in Athens. It was known from the 1961 excavations that the deposit to be explored was a very shallow one—only a little more than two feet thick at its deepest. This layer was composed partly of accumulated occupation debris but mainly of collapsed and disintegrated mud walls from the site's ancient buildings. Shallow plowing in modern times had disturbed the top four or five inches of the deposit, with the result that only 18 inches or so of undisturbed early Neolithic material remained. The digging began in



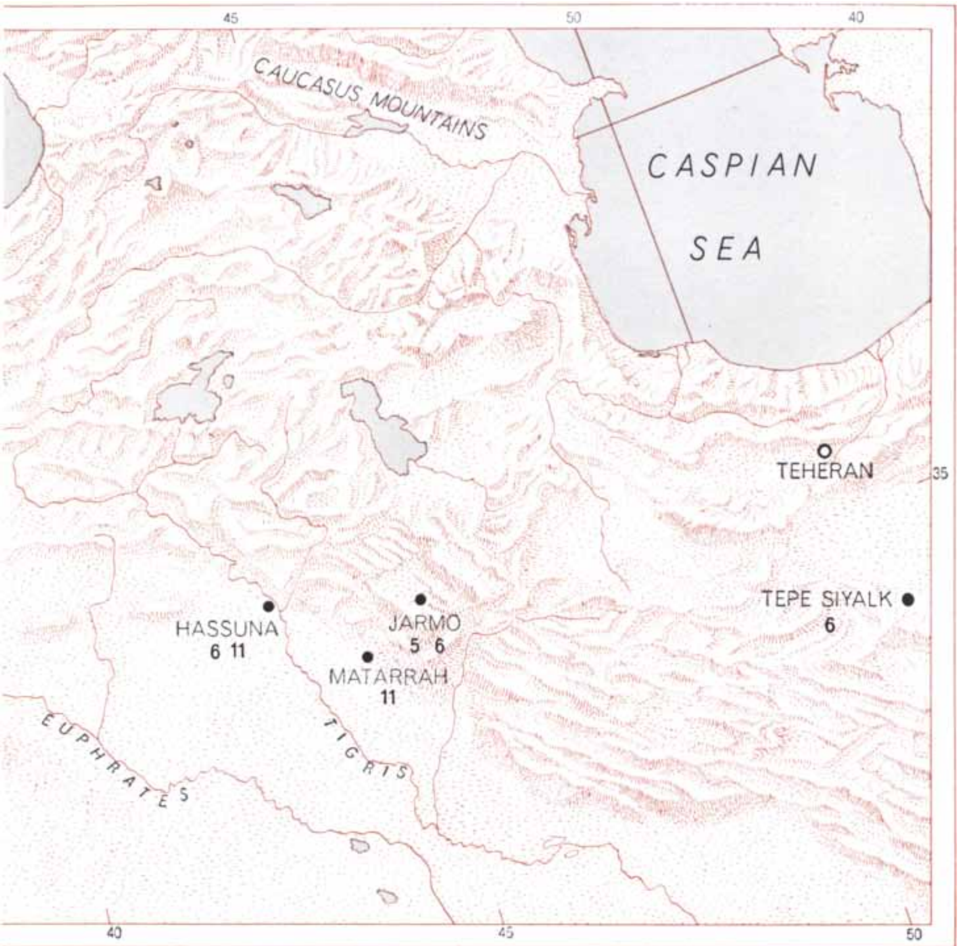
CULTURAL SIMILARITIES between Nea Nikomedeia and other early sites in Europe, Asia Minor and the Middle East are indicated by the numbers at each place name. Among the European sites, Karanovo in central Bulgaria is representative of the many Neolithic villages in that northern region; Soufli Magoula and Sesklo in central Greece similarly typify the early sites to the

early June; when it ended in October, this thin layer had been excavated over an area of about half an acre.

Archaeological techniques of the kind normally used in excavating stone or brick buildings could not be applied here. The clay that forms the subsoil at Nea Nikomedeia is the same material the early settlers used to make the walls of their houses; consequently this clay also made up the bulk of the layer being excavated. Any details of ancient structures preserved in the deposit—such as the foundations of walls or the holes that contained timber uprights—would appear only as faint discolorations in the clay. To detect these discolorations and define their outlines clearly it was necessary to apply the painstaking technique of scraping. As the term indicates, scraping involves the removal of wide areas of soil a fraction of an inch at a time. The entire section of the mound to be excavated was laid out in a grid of 12-foot squares; as digging progressed, several adjacent squares would be scraped simultaneously and the pattern of the discolorations noted. All the walls and postholes found at Nea Nikomedeia, as well as the storage and rubbish pits associated with them, were uncovered in this way [*see bottom illustration on page 82*].

The whole of the mound was not opened during the 1963 season, and some house outlines that continued into the unexcavated portions of the site are not completely revealed. What has been exposed, however, makes it evident that the settlement consisted of individual buildings situated two to five yards apart on a slight knoll at the edge of what was then a marshy lake or inlet. There were two periods of early Neolithic building at Nea Nikomedeia. They are separated in places by a deposit of what appears to be the beginning of a humus soil, so that the second building period evidently represents a reoccupation of the site after a period of abandonment. In any case, the earlier settlement was the smaller of the two, and it was surrounded by a pair of concentric walls on the landward side of the knoll. At the time of the second building period the settlement expanded up to the limit of these walls, which were then replaced by a deep ditch. The ditch shows evidence of having been filled with water; perhaps it served as a moat.

Seven major structures of the earlier building period were uncovered in 1963; six of them are most likely dwellings. Carbonized remains of wood indicate that the frames of the houses were made of oak. The mud walls of the buildings were constructed in the following manner: Sapling uprights were set in place three to four feet apart and the space between them was filled in with bundles of reeds standing on end. The reeds were then plastered on the inside surface with mud mixed with chaff and on the outside with white clay. Many of the footings both for the walls and for the roof supports were



PARALLELS TO NEA NIKOMEDEIA

ARCHITECTURE
1 SQUARE HOUSE PLAN
2 WOOD FRAME AND MUD WALL
3 OPEN SETTLEMENT PLAN

SUBSISTENCE
4 CATTLE?
5 PIGS?

ADORNMENT
6 STUDS AND NAILS
7 CLAY STAMPS
8 BELT-FASTENER

POTTERY DECORATION
9 WHITE-PAINTED AND FINGER-IMPRESSED
10 RED-ON-CREAM PAINTING
11 MODELED FACE

south. These two areas, the nearest to Nea Nikomedeia, possess the largest number of traits in common with it. Nea Nikomedeia thus exhibits a distinct European character, although it has traits in common with sites as distant as Tepe Siyalk. This suggests that southeastern Europe was not peripheral to the region within which the Neolithic revolution began but was an integral part of it.

made a yard or so deep, evidently to ensure that the buildings would not be affected by frost heave or by the wetness of the waterfront subsoil. Because the mud-plastered walls would have been subject to damage by rain, it is assumed that the houses of Nea Nikomedeia had peaked and thatched roofs with overhanging eaves that would carry off rainwater [*see illustration on page 87*].

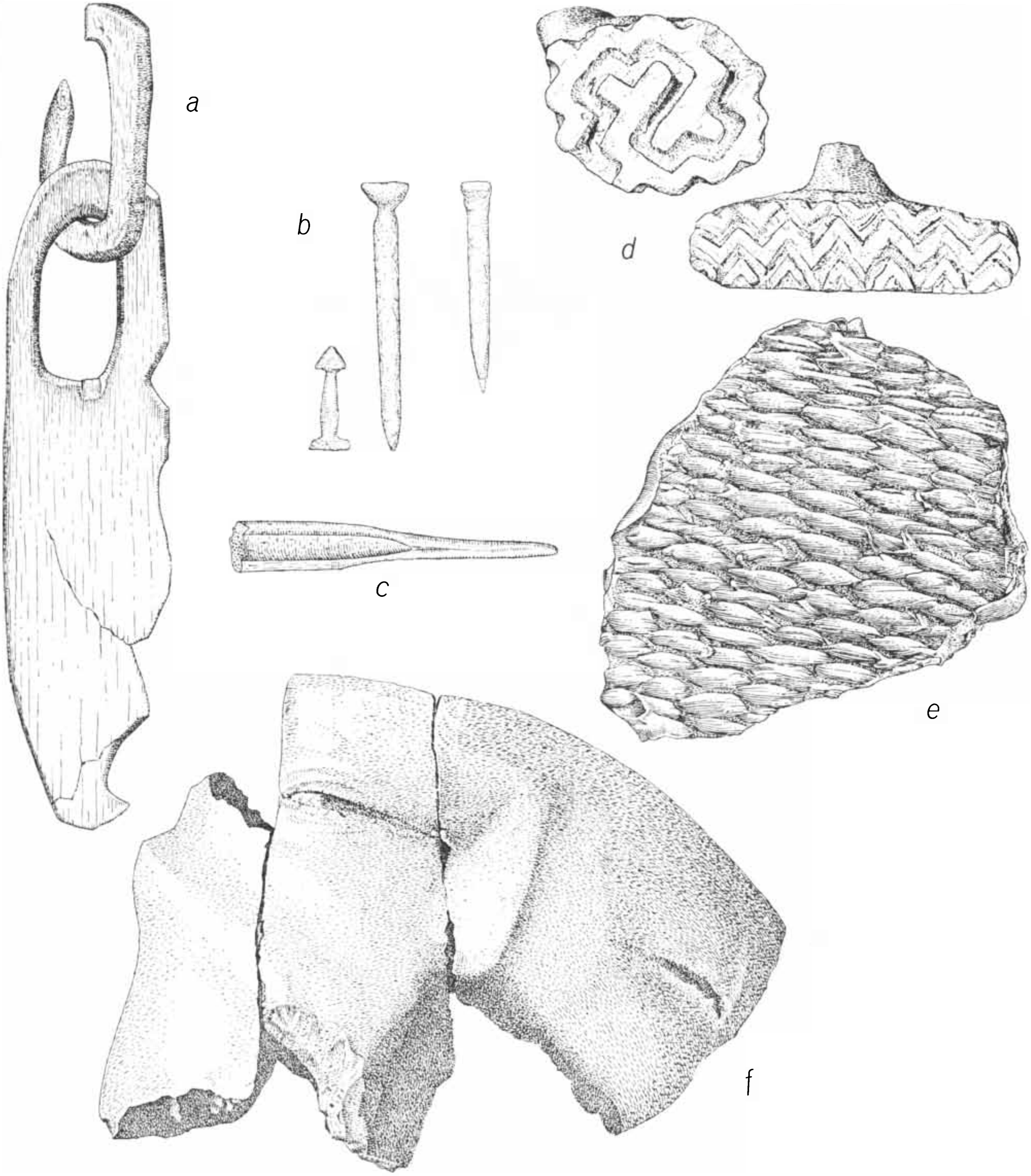
Although the six house plans are different, they have several features in common. The basic unit was evidently a square about 25 feet to a side. Two one-room houses show exactly these dimensions. A third building, consisting of a large main room and a narrow room along one side, was 25 feet wide; its full length could not be determined. The same plan—a large main room with a narrow room attached—is also found in the best-preserved dwelling uncovered at Nea Nikomedeia. At one end of the narrow room in this house stood a raised platform of plaster into which were sunk a hearth basin and a storage bin; on the opposite side of the house was a fenced-off porch area.

A considerably larger structure, some 40 feet square and divided into three parts by parallel rows of heavy timbers, is also attributable to the first building period at Nea Nikomedeia. It was uncovered in the part of the excavation closest to the center of the mound. Five figurines of women were found within the bounds of its walls. Both its size and its contents suggest that the building served some ritual purpose.

Although much analytical work still remains to be done, preliminary findings by the botanists and zoologists who are working with the expedition provide a good outline of the economy of this early Neolithic community. The fact that the farmers of the first settlement grew wheat, barley and lentils is indicated by carbonized material; the particular varieties of these plants have not yet been identified. A study of the animal bones recovered in 1961, together with a preliminary analysis of some 25,000 additional specimens recovered in 1963, suggest that sheep and goats played the primary role in animal husbandry. The bones of pigs and cattle were also present, but in far fewer numbers. In addition to tending their flocks the people of Nea Nikomedeia engaged in hunting, fowling and fishing. Deer, hare and wild pig were among the game animals; the presence of fish bones and the shells of both saltwater cockles and freshwater mussels shows that the early settlers also exploited the resources of their coastal environment.

Assuming that the carbon-14 date for Nea Nikomedeia is correct, evidence for the presence of even limited numbers of domesticated cattle and pigs at the site is a matter of considerable importance in the record of animal domestication. For one thing, this would be the earliest dated occurrence of domesticated cattle yet known anywhere in the world. If taken together with the possible evidence of cattle domestication at Fikirtepe in northwestern Turkey and at Çatal Hüyük in southeastern Turkey, this finding would argue for an original center for the domestication of cattle in Asia Minor and southeastern Europe. As for pigs, so early an occurrence of pig bones in Greece suggests that there may have been an independent European center for the domestication of these animals, unconnected with the center implied for the Middle East by the animal-bone findings at such early village sites as Jarmo in Iraq.

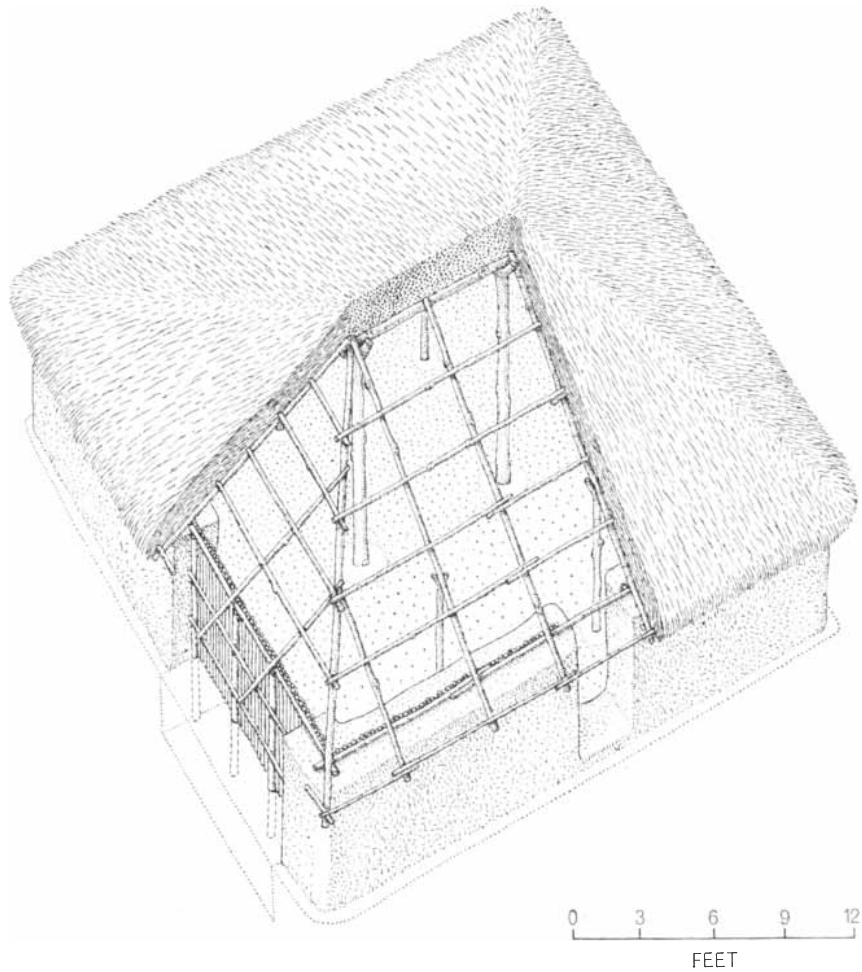
It remains possible, although not probable, that the bones of both cattle and pigs found at Nea Nikomedeia represent hunters' prey rather than herdsmen's produce. The remains of both species recovered in 1961 do not all indicate the age of the animal. Of



EARLY NEOLITHIC SKILLS in working with four varieties of raw material are demonstrated in this illustration. The hook-and-eye belt-fastener (*a*) and the awl (*c*) are made of bone. The two marble nails and the serpentine stud (*b*) show a capacity for fine lapidary work. Examples of the potter's art include geometric stamps (*d*), probably for body-painting, and a human face modeled below the rim of a pot (*f*). The bit of twined matting (*e*) was accidentally preserved in clay. All objects are shown natural size.

the bones that do indicate age, however, more than half belonged to immature animals; only under exceptional circumstances would such a high proportion of young animals be killed as a result of hunting. Nonetheless, the final word on cattle- and pig-domestication at this early Neolithic site must be postponed until the analysis of the vastly larger sample of bones uncovered in 1963 has been completed.

Regardless of the ultimate verdict on this point, it is evident that the economy of Nea Nikomedeia rested on a fourfold base, with wheat and barley as the major cereal crops, and sheep and goats as sources of meat and presumably of hides and milk. There is no reason to doubt that the first inspiration for the cultivation of these cereals and the husbanding of these animals came to Europe from the Middle East, although as yet the earliest links connecting the two regions have not been discovered. The essentials of the economy at Nea Nikomedeia, then, were foreign in origin; what about the other elements of village life? In reflecting on the settlement's tools, pottery, articles of personal adornment and ritual objects, one seeks similarities to material from other sites in Europe and abroad. In this way what was unique at Nea Nikomedeia can be distinguished from what was derived from—or perhaps contributed to—other areas.



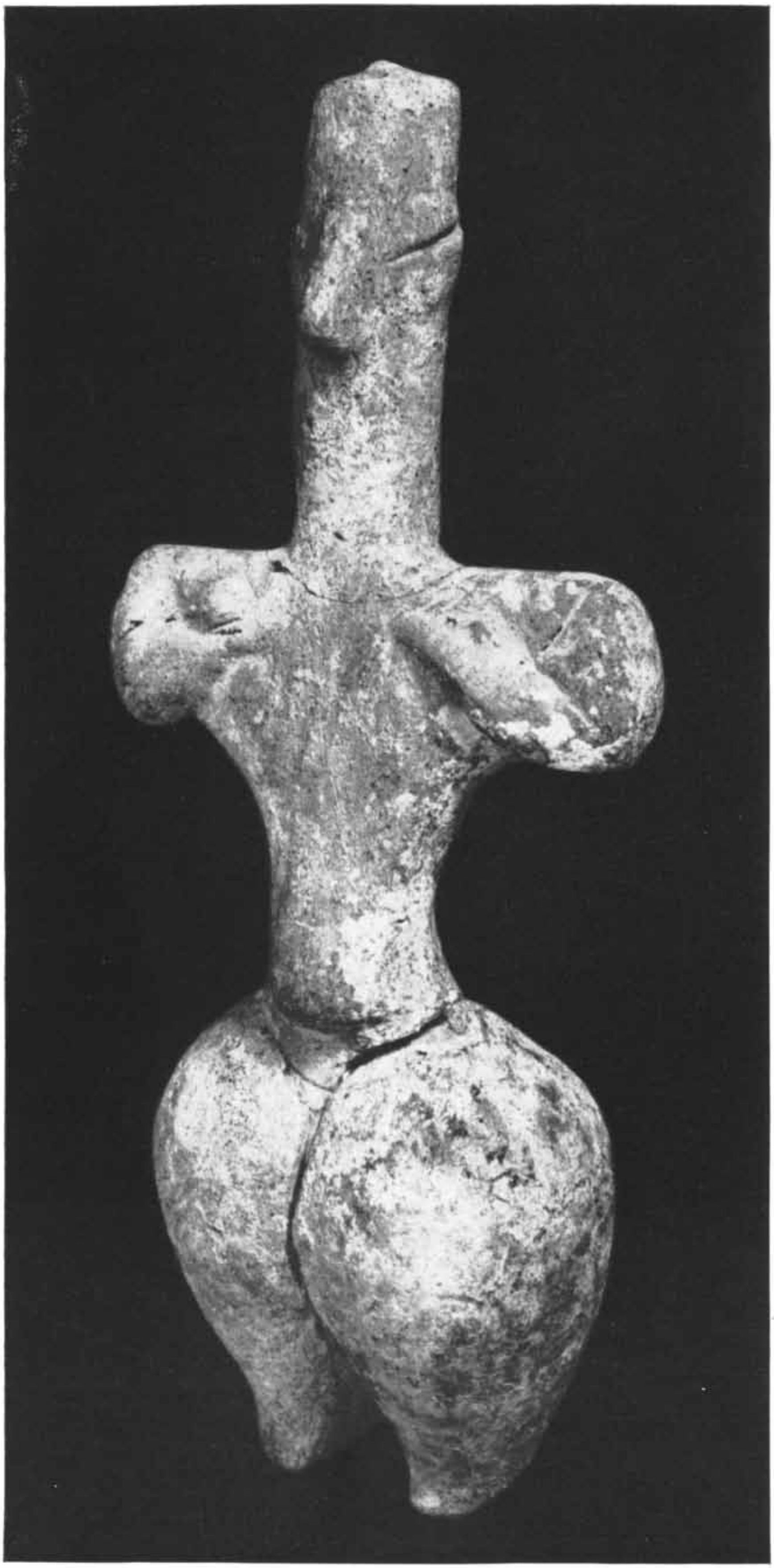
EARLY NEOLITHIC DWELLING consisted of timber uprights inside thick walls of clay plastered onto a frame of saplings and reeds. The foundations for the wall and the footings for the uprights were dug some three feet deep. The peaked pole-and-thatch roof, supported by crotched uprights, is hypothetical, but similar roofs are still built in Greece.

The tool kit of the first settlers included both the classic artifacts of polished stone—axes, adzes and chisels—that originally gave the Neolithic, or New Stone, age its name, and a variety of chipped blades of flint and chert from which the farmers made scrapers, arrowheads and the cutting edges of rude sickles. The bow and arrow and the sling were among the hunters' weapons; hundreds of clay slingstones have been unearthed. The settlers also made bone needles (possibly including net-making needles), awls and fishhooks. Such a list, with a few exceptions or additions, would be typical of any other nearly contemporary community in southeastern Europe, Asia Minor or the Middle East. Nonetheless, there are consistent local traditions; as an example, the chipped stone artifacts from Nea Nikomedeia resemble those from sites in central Greece, eastern Yugoslavia and central Bulgaria and differ from those found in southern Greece, Asia Minor and the Middle East.

The earliest pottery at the site shows great technical competence in manufacture, in the range of vessel shapes and in decoration. The settlers made open bowls, large narrow-mouthed storage jars, small ladles, miniature vessels and peculiar shoe-shaped pots that may have been put into a bed of coals to heat their contents. Many of the smaller bowls were provided with lugs, which are perforated vertically or horizontally, so that they could be suspended by cords. Almost all the pots have thin walls and bases that are ring-shaped or disk-shaped. The potters decorated some of their wares by painting and some with finger impressions on the outside surface.

The earliest-known phases of Neolithic settlement in central Bulgaria and eastern Yugoslavia are characterized by pottery that bears finger-impressed decorations or designs in white paint; examples of both can be found at Nea Nikomedeia, but neither is common. That they are found at all, however, lends weight to the conclusion that connecting links of some kind existed between these early Macedonian farmers and those to the north. The pottery evidence indicates even closer ties between Nea Nikomedeia and the earliest pottery-using settlements in central Greece. Both there and at Nea Nikomedeia wares decorated with block designs, triangles and patterns of wavy lines—all painted in red on a cream-colored background—are commonplace.

These pottery motifs provide an example of the ways in which Nea Nikomedeia may have contributed culturally to areas outside Europe. The tradition of painting pottery with red designs on a cream-colored background appears several hundred years later in southern Asia Minor with the beginnings of the Hacilar culture [see "Hacilar: A Neolithic Village Site," by James Mellaart; Scientific American, August, 1961]. By the same token, some of the



FIGURINE OF A WOMAN, seven inches high, is one of five similar clay sculptures unearthed inside the largest early building at Nea Nikomedeia. The presence of so many figurines, which are presumably fertility symbols, suggests that building was used ritually.

pots of Nea Nikomedeia are decorated with human faces made by pinching up a "nose" and adding ovals of clay as "eyes." Similarly decorated pots have been found in post-Neolithic levels at Hacilar and also at the earlier sites of Hassuna and Matarrah in Iraq. In the absence of well-defined intermediate steps, it must remain a matter of conjecture whether or not the presence of pots with human faces at these widely separated sites represents the diffusion of an idea or an independent invention.

Both European and Asiatic characteristics can be found among the articles of personal adornment at Nea Nikomedeia. A bone belt-fastener with a hook-and-eye clasp was uncovered during the 1963 season; a number of such fasteners have been found in the early Neolithic levels at Çatal Hüyük. A bone hook from Soufli Magoula, an early Neolithic site in central Greece, may be another European example of the same kind of object. Clay stamps, each exhibiting a different geometric pattern, are relatively common at Nea Nikomedeia; similar stamps are known from central Greece and elsewhere in southeastern and central Europe. Some of the stamps found at Nea Nikomedeia, however, have designs similar to those on stamps from Çatal Hüyük.

Some Neolithic sites in the Middle East—Tell Judeideh in Syria, Jarmo and Hassuna in Iraq and Tepe Siyalk in Iran—contain curious stone objects that look somewhat like primitive nails. The excavations at Nea Nikomedeia have yielded a great number of these objects, neatly wrought out of white marble, and a lesser number of tiny studs made of green serpentine. It is probable that the nails were headdress decorations and that the studs were earplugs. Such carefully shaped and polished articles of marble and serpentine represent a high level of technical achievement.

Of particular interest is the fact that the settlers made clay figurines of men and women; these stylized sculptures reflect a high level of artistic sensibility. The more sophisticated figurines were made in sections and then pegged together before they hardened; the component parts are the head, the torso (including the arms) and two separate legs. The head usually consists of a slightly flattened cylinder from which a prominent pointed nose is pinched up; as with the faces on the pots, the eyes are often represented by applied lumps of clay. Figurines of women outnumber those of men; in the commonest type of

female figurine the thighs are modeled to an exaggerated roundness. The breasts are mere knobs, supported by the hands [*see illustration on page 88*].

Other clay figurines include rather less elegant models of sheep and goats. It is puzzling that these economically important animals are rendered with such relative crudity whereas three effigies of frogs found at Nea Nikomedeia were beautifully carved in green and blue serpentine and then polished. The site's marshy locale makes it reasonable to suppose that its inhabitants were well acquainted with these amphibians, but what significance the frog may have possessed that inspired the execution of its portrait in stone is unknown.

It is commonly assumed that early societies engaged in the newly discovered art of food production soon developed beliefs about the supernatural in which human, animal and plant fertility were emphasized. The exaggerated forms of the figurines of women uncovered at Nea Nikomedeia, together with the fact that five of them were found together within the confines of the site's largest structure, seem to indicate that fertility beliefs played a part in the life of this particular Neolithic community. The excavations have provided a further insight into the community's spiritual views: There was evidently little or no regard for the dead. Burial pits were located outside the house walls and sometimes in the debris of buildings that had fallen into disuse; the inhabitants appear to have taken little trouble to prepare the graves. In some instances one gains the impression that the dead were crammed into a barely adequate depression. No personal adornment, food offerings or grave goods have been found with the skeletons. In one enigmatic instance, however, a skeleton was found with a large pebble thrust between its jaws.

In summary, the characteristics of early Neolithic village life as it was practiced by the farmers of Nea Nikomedeia show basic parallels with life in similar Neolithic villages in Asia Minor and the Middle East. The most telling of these parallels are the very roots of the Neolithic revolution itself: the cultivation of wheat and barley and the domestication of sheep and goats. This village in the Macedonian marshes, however, was no mere foothold established in Europe by pioneers from the Middle East. Village plans, house plans and building methods comparable to those used at Nea Nikomedeia are known from two nearby regions. The first of these regions includes the early Neolithic sites of Karanovo and Azmak in central Bulgaria; parts of plans of

SKELETON OF ADULT, who had been buried in a contracted position, had a large, flat pebble inserted between the jaws for some unknown purpose. The burials at Nea Nikomedeia do not include funeral offerings, and the graves are cramped and shallow.

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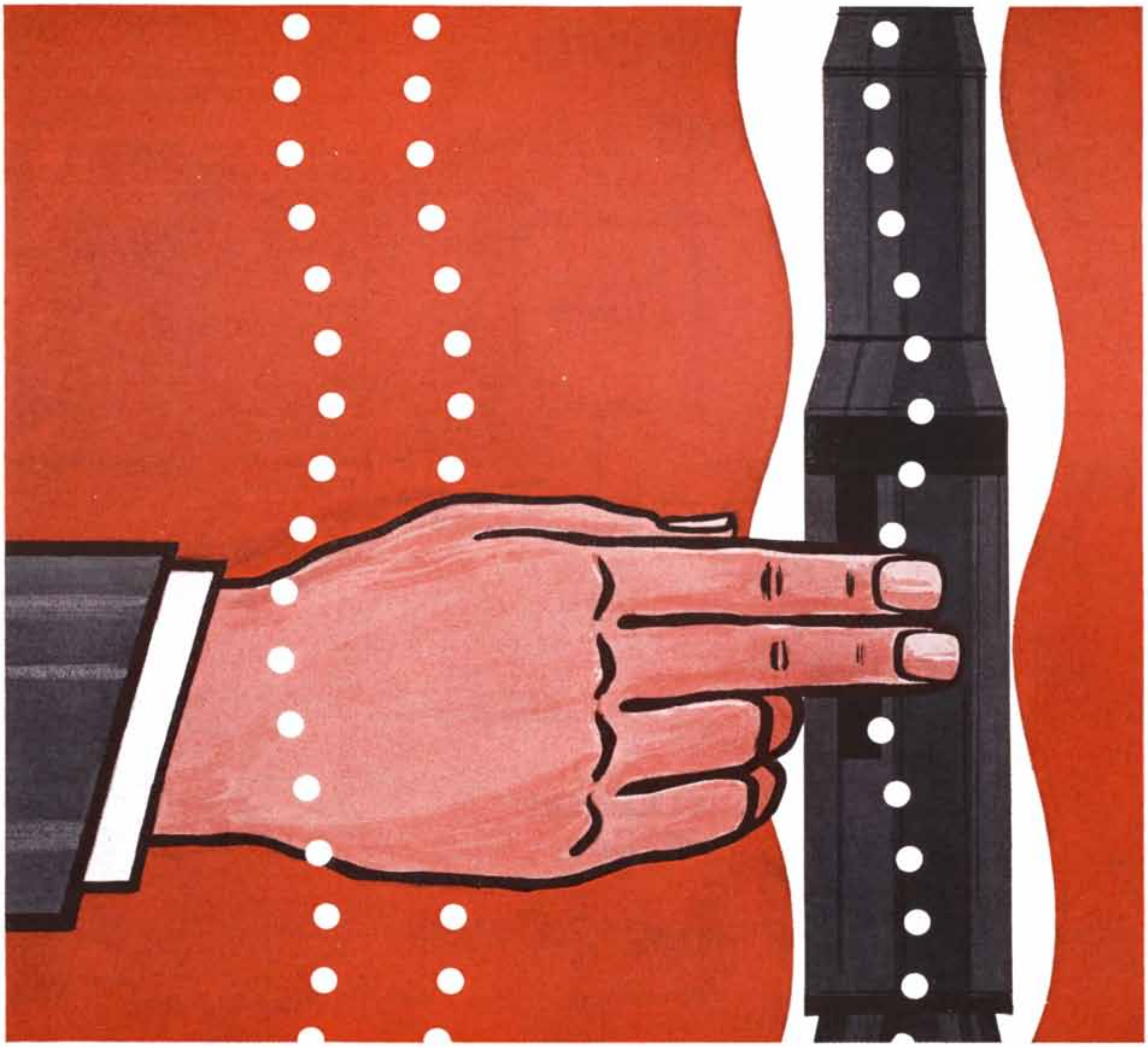

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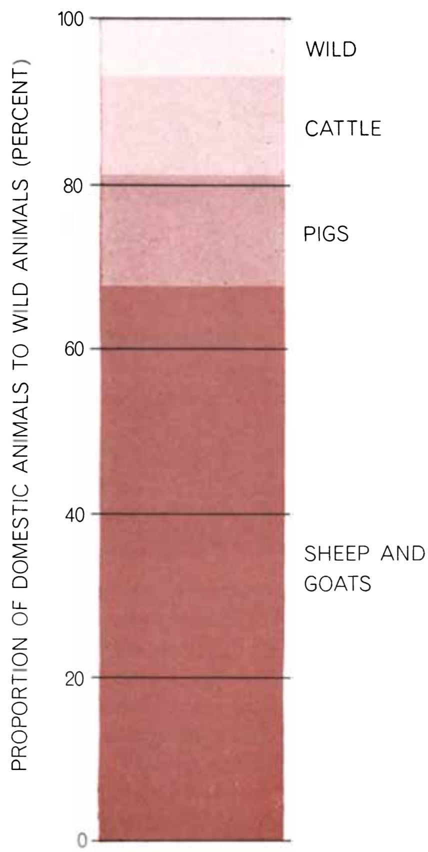
GT&E SUBSIDIARIES: Telephone Operating Cos. • GT&E Laboratories • GT&E International • General Telephone Directory • Automatic Electric • Lenkurt Electric • Sylvania Electric Products similar houses have also been exposed at several of the early sites in central Greece. It seems probable, therefore, that a Neolithic pattern of life characterized by a well-established architectural tradition adapted to the European environment and locally available materials stands behind the finds both at Nea Nikomedeia and at the sites of these other early settlements in southeastern Europe.

The precise origins of this architectural tradition remain unknown, but it is one that contrasts strongly with the custom of building houses one against another around the nucleus of a courtyard, which dominates village construction in Asia Minor and the Middle East during the late seventh millennium and early sixth millennium B.C. In the last analysis, such evidence may mean that southeastern Europe will have to be considered a part of that zone—heretofore generally deemed to lie exclusively in Asia Minor and the Middle East—in which were made the primary discoveries that led to the development of Old World civilization.



PARTIAL ANALYSIS of animal bones at Nea Nikomedeia shows the preponderance of sheep and goats. If cattle and pigs were domestic rather than wild animals, hunting provided less than 10 percent of the animal produce consumed by the villagers.

MOTHS AND ULTRASOUND

Certain moths can hear the ultrasonic cries by which bats locate their prey. The news is sent from ear to central nervous system by only two fibers. These can be tapped and the message decoded

by Kenneth D. Roeder

If an animal is to survive, it must be able to perceive and react to predators or prey. What nerve mechanisms are used when one animal reacts to the presence of another? Those animals that have a central nervous system perceive the outer world through an array of sense organs connected with the brain by many thousands of nerve fibers. Their reactions are expressed as critically timed sequences of nerve impulses traveling along motor nerve fibers to specific muscles. Exactly how the nervous system converts a particular pattern of sensory input into a specific pattern of motor output remains a subject of investigation in many branches of zoology, physiology and psychology.

Even with the best available techniques one can simultaneously follow the traffic of nerve impulses in only five or perhaps 10 of the many thousands of separate nerve fibers connecting a mammalian sense organ with the brain. Trying to learn how information is encoded and reported among all the fibers by following the activity of so few is akin to basing a public opinion poll on one or two interviews. (Following the activity of all the fibers would of course be like sampling public opinion by having the members of the population give their different answers in chorus.) Advances in technique may eventually make it possible to follow the traffic in thousands of fibers; in the meantime much can be learned by studying animals with less profusely innervated sense organs.

With several colleagues and students at Tufts University I have for some time been trying to decode the sensory patterns connecting the ear and central nervous system of certain nocturnal moths that have only two sense cells in each ear. Much of the behavior of these simple invertebrates is built in, not learned, and therefore is quite stereotyped and stable under experimental conditions. Working with these moths offers another advantage: because they depend on their ears to detect their principal predators, insect-eating bats, we are able to discern in a few cells the nervous mechanisms on which the moth's survival depends.

Insectivorous bats are able to find their prey while flying in complete darkness by emitting a series of ultrasonic cries and locating the direction and distance of sources of echoes. So highly sophisticated is this sonar that it enables the bats to find and capture flying insects smaller than mosquitoes. Some night-flying moths—notably members of the families Noctuidae, Geometridae and Arctiidae—have ears that can detect the bats' ultrasonic cries. When they hear the approach of a bat, these moths take evasive action, abandoning their usual cruising flight to go into sharp dives or erratic loops or to fly at top speed directly away from the source of ultrasound. Asher E. Treat of the College of the City of New York has demonstrated that moths taking evasive action on a bat's approach have a significantly higher chance of survival than those that continue on course.

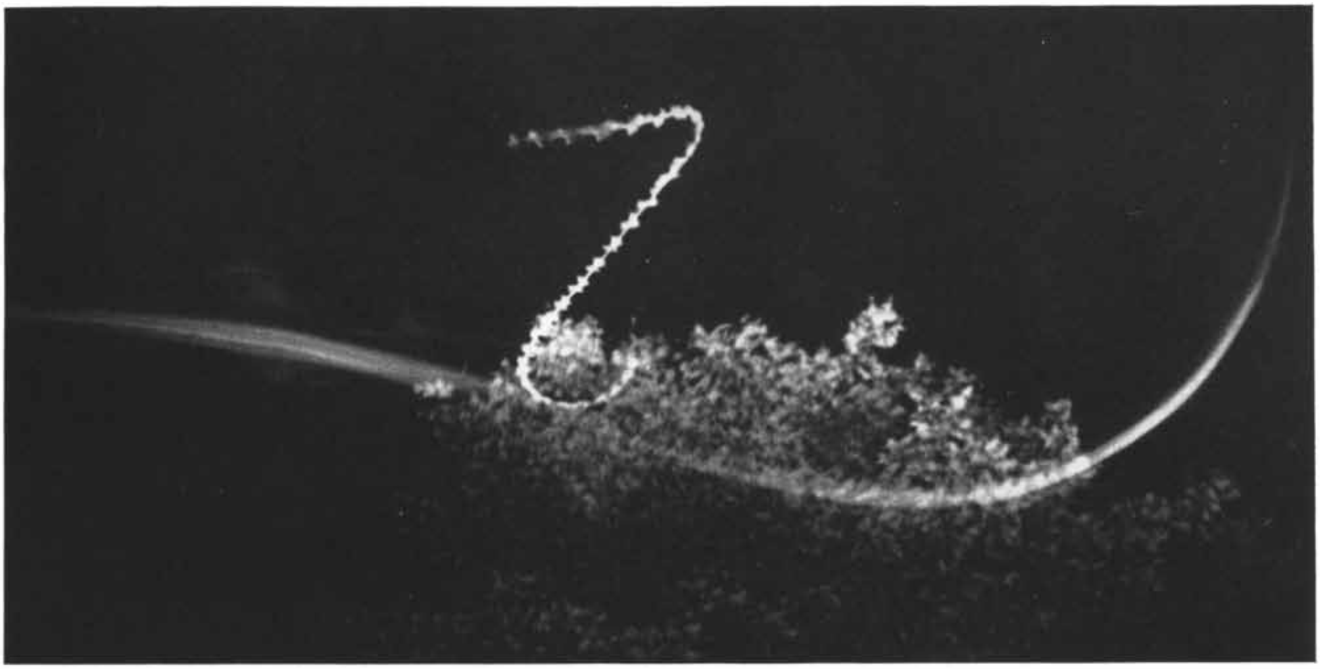
A moth's ears are located on the sides of the rear part of its thorax and are directed outward and backward into the constriction that separates the thorax and the abdomen [*see top illustration on page 96*]. Each ear is externally visible as a small cavity, and within the cavity is a transparent eardrum. Behind the eardrum is the tympanic air sac; a fine strand of tissue containing the sensory apparatus extends across the air sac from the center of the eardrum to a skeletal support. Two acoustic cells, known as *A* cells, are located within this strand. Each *A* cell sends a fine sensory strand outward to the eardrum and a nerve fiber inward to the skeletal support. The two *A* fibers pass close to a large nonacoustic cell, the *B* cell, and are joined by its nerve fiber. The three fibers continue as the tympanic nerve into the central nervous system of the moth. From the two *A* fibers, then, it is possible—and well within our technical means—to obtain all the information about ultrasound that is transmitted from the moth's ear to its central nervous system.

Nerve impulses in single nerve fibers can be detected as "action potentials," or self-propagating electrical transients, that have a magnitude of a few millivolts and at any one point on the fiber last less than a millisecond. In the moth's *A* fibers action potentials travel from the sense cells to the central nervous system in less than two milliseconds. Action potentials are normally an all-or-nothing phenomenon; once initiated by the sense cell, they travel to the end of the nerve fiber. They can be detected on the outside of the fiber by means of fine electrodes, and they are displayed as "spikes" on the screen of an oscilloscope.

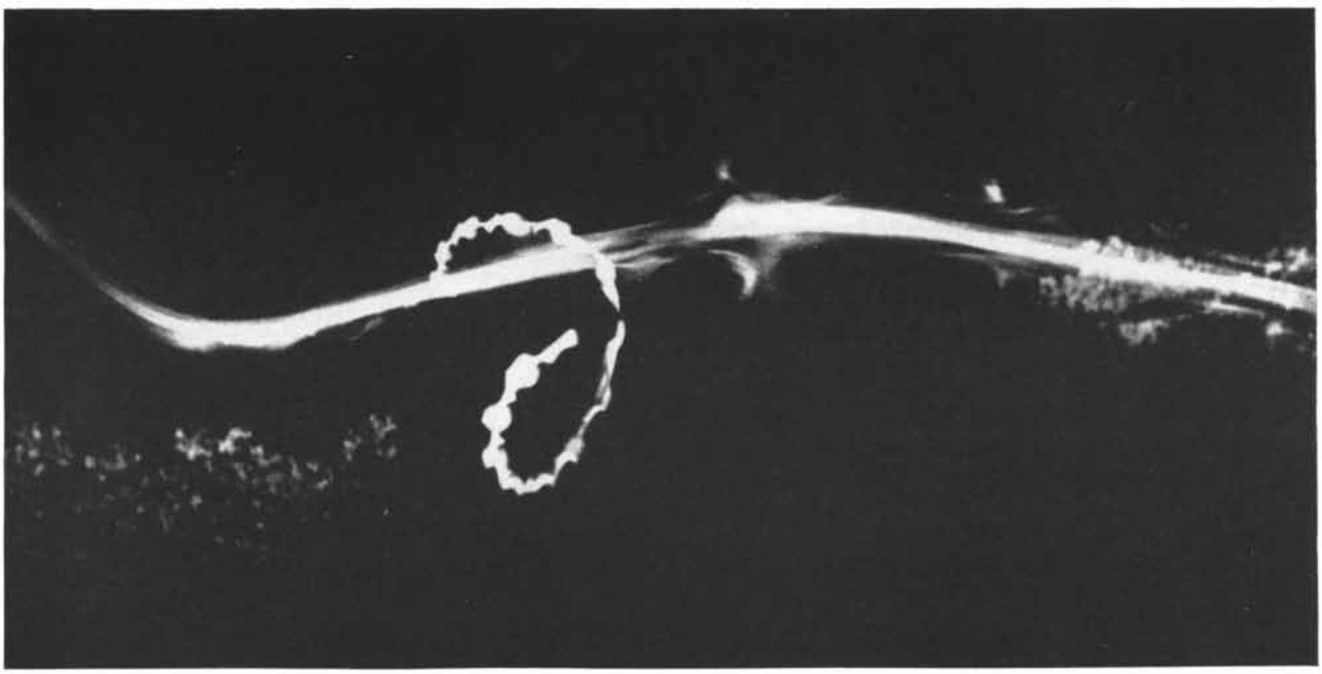
Tympanic-nerve signals are demonstrated in the following way. A moth, for example the adult insect of one of the common cutworms or armyworms, is immobilized on the stage of a microscope. Some of its muscles are dissected away to expose the tympanic nerves at a point outside the central nervous system. Fine silver hooks are placed under one or both nerves, and the pattern of passing action potentials is observed on the oscilloscope. With moths thus prepared we have spent much time in impromptu outdoor laboratories, where the cries of passing bats provided the necessary stimuli.

In order to make precise measurements we needed a controllable source of ultrasonic pulses for purposes of comparison. Such pulses can be generated by electronic gear to approximate natural bat cries in frequency and duration. The natural cries are frequency-modulated: their frequency drops from about 70 kilocycles per second at the beginning of each cry to some 35 kilocycles at the end. Their duration ranges from one to 10 milliseconds, and they are repeated from 10 to 100 times a second. Our artificial stimulus is a facsimile of an average series of bat cries; it is not frequency-modulated, but such modulation is not detected by the moth's ear. Our sound pulses can be accurately graded in intensity by decibel steps; in the sonic range a decibel is roughly equivalent to the barely noticeable difference to human ears in the intensity of two sounds.

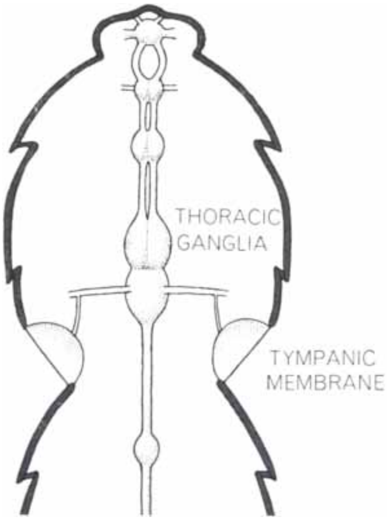
By using electronic apparatus to elicit and follow the responses of the *A* cells we have been able to define the amount of acoustic information avail-

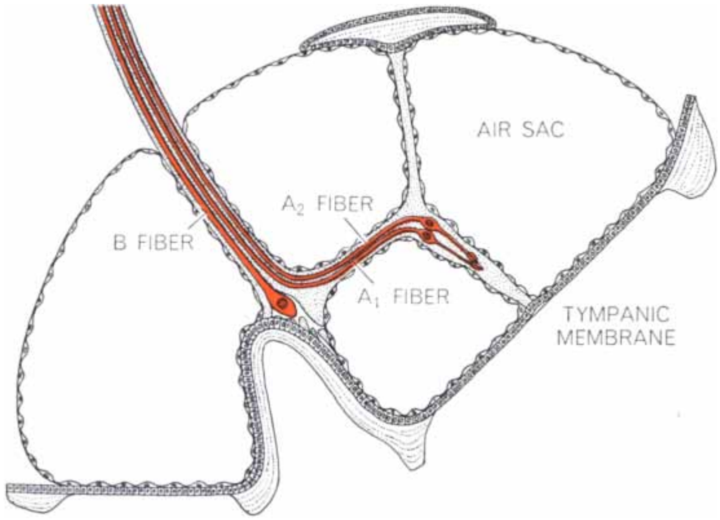


MOTH EVADED BAT by soaring upward just as the bat closed in to capture it. The bat entered the field at right; the path of its flight is the broad white streak across the photograph. The smaller white streak shows the flight of the moth. A tree is in background. The shutter of the camera was left open as contest began. Illumination came from continuous light source below field.



BAT CAPTURED MOTH at point where two white streaks intersect. Small streak shows the flight pattern of the moth. Broad streak shows the flight path of the bat. Both streak photographs were made by Frederic Webster of the Sensory Systems Laboratories.



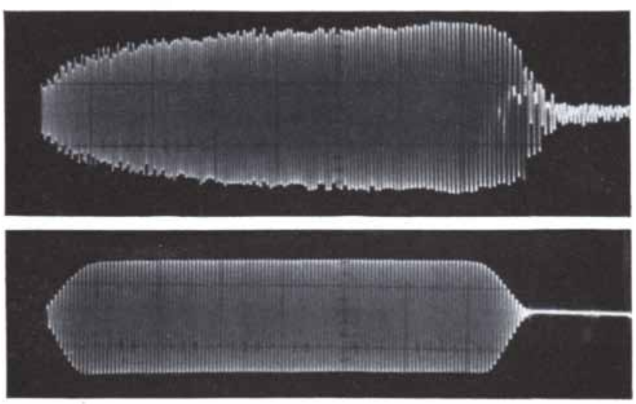


NERVES FROM EAR to central nervous system of moth are shown at two magnifications. Drawing at left indicates position of the tympanic organs on each side of the moth and the tympanic nerves connecting them with the thoracic ganglia. Central nervous system is colored. Drawing at right shows two nerve fibers of the acoustic cells joined by a nonacoustic fiber to form the tympanic nerve.

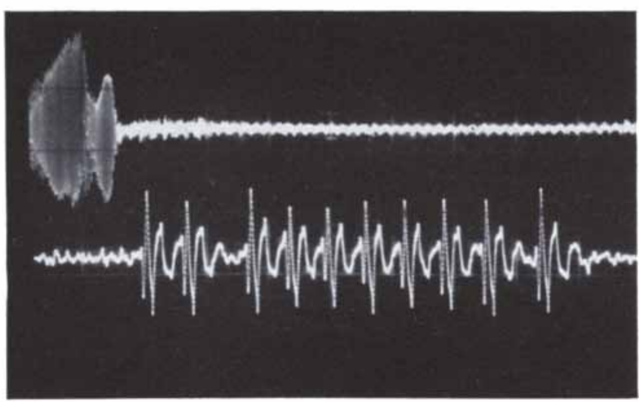
able to the moth by way of its tympanic nerve. It appears that the tympanic organ is not particularly sensitive; to elicit any response from the *A* cell requires ultrasound roughly 100 times more intense than sound that can just be heard by human ears. The ear of a moth can nonetheless pick up at distances of more than 100 feet ultrasonic bat cries we cannot hear at all. The reason it cannot detect frequency modulation is simply that it cannot discriminate one frequency from another; it is tone-deaf. It can, however, detect frequencies from 10 kilocycles to well over 100 kilocycles per second, which covers the range of bat cries. Its greatest talents are the detection of pulsed sound—short bursts of sound with intervening silence—and the discrimination of differences in the loudness of sound pulses.

When the ear of a moth is stimulated by the cry of a bat, real or artificial, spikes indicating the activity of the *A* cell appear on the oscilloscope in various configurations. As the stimulus increases in intensity several changes are apparent. First, the number of *A* spikes increases. Second, the time interval between the spikes decreases. Third, the spikes that had first appeared only on the record of one *A* fiber (the "A_1" fiber, which is about 20 decibels more sensitive than the A_2 fiber) now appear on the records of both fibers. Fourth, the greater the intensity of the stimulus, the sooner the *A* cell generates a spike in response.

The moth's ears transmit to the oscilloscope the same configuration of spikes they transmit normally to the central nervous system, and therein lies our interest. Which of the changes in auditory response to an increasingly intense stimulus actually serve the moth as criteria for determining its behavior under natural conditions? Before we face up to this question let us speculate on the possible significance of these criteria from the viewpoint of the moth. For the moth to rely on the first kind of information—the number of *A* spikes—might lead it into a fatal error: the long, faint cry of a bat at a distance could be confused with the short, intense cry of a bat closing for the kill. This error could be avoided if the moth used the second kind of information—the interval between spikes—for estimating the loudness of the bat's cry. The third kind of information—the activity of the A_2 fiber—might serve to change an "early warning" message to a "take cover" message. The fourth kind of information—the length of time it takes for a spike to be generated—might provide the moth with



OSCILLOSCOPE TRACES of a real bat cry (*top*) and a pulse of sound generated electronically (*bottom*) are compared. The two ultrasonic pulses are of equal duration (length), 2.5 milliseconds, but differ in that the artificial pulse has a uniform frequency.



BAT CRY AND MOTH RESPONSE were traced on same oscilloscope from tape recording by Webster. The bat cry, detected by microphone, yielded the pattern at left in top trace. Reaction of the moth's acoustic cells produced the row of spikes at bottom.

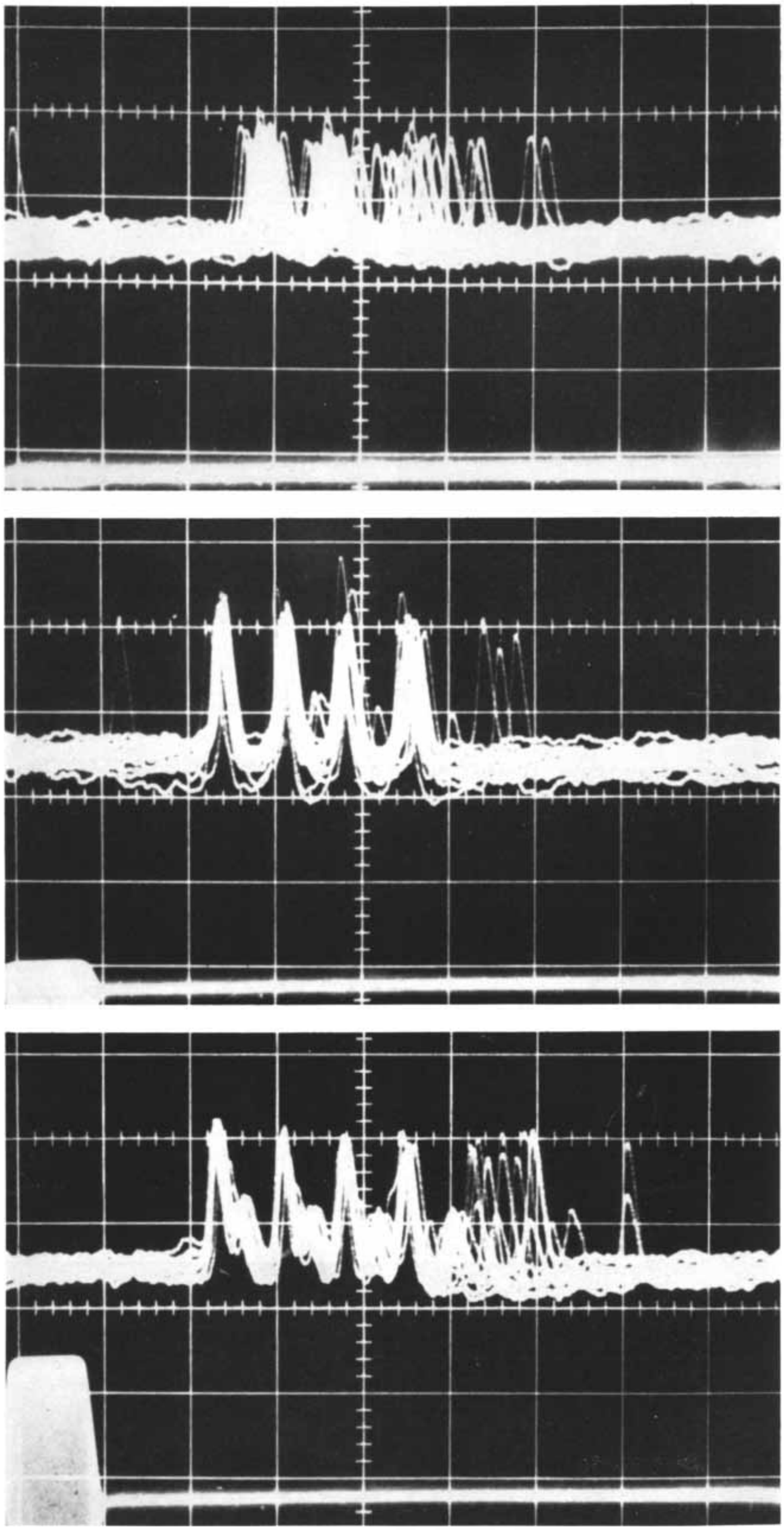
the means for locating a cruising bat; for example, if the sound was louder in the moth's left ear than in its right, then *A* spikes would reach the left side of the central nervous system a fraction of a millisecond sooner than the right side.

Speculations of this sort are profitable only if they suggest experiments to prove or disprove them. Our tympanic-nerve studies led to field experiments designed to find out what moths do when they are exposed to batlike sounds from a loudspeaker. In the first such study moths were tracked by streak photography, a technique in which the shutter of a camera is left open as the subject passes by. As free-flying moths approached the area on which our camera was trained they were exposed to a series of ultrasonic pulses.

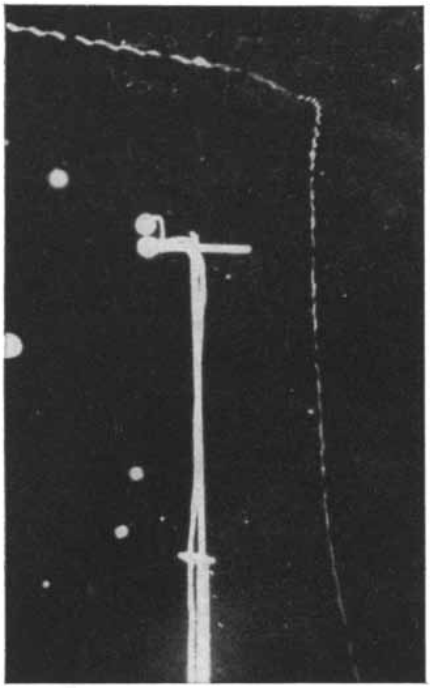
More than 1,000 tracks were recorded in this way. The moths were of many species; since they were free and going about their natural affairs most of them could not be captured and identified. This was an unavoidable disadvantage; earlier observations of moths captured, identified and then released in an enclosure revealed nothing. The moths were apparently "flying scared" from the beginning, and the ultrasound did not affect their behavior. Hence all comers were tracked in the field.

Because moths of some families lack ears, a certain percentage of the moths failed to react to the loudspeaker. The variety of maneuvers among the moths that did react was quite unpredictable and bewildering [*see illustrations at top of next page*]. Since the evasive behavior presumably evolved for the purpose of bewildering bats, it is hardly surprising that another mammal should find it confusing! The moths that flew close to the loudspeaker and encountered high-intensity ultrasound would maneuver toward the ground either by dropping passively with their wings closed, by power dives, by vertical and horizontal turns and loops or by various combinations of these evasive movements.

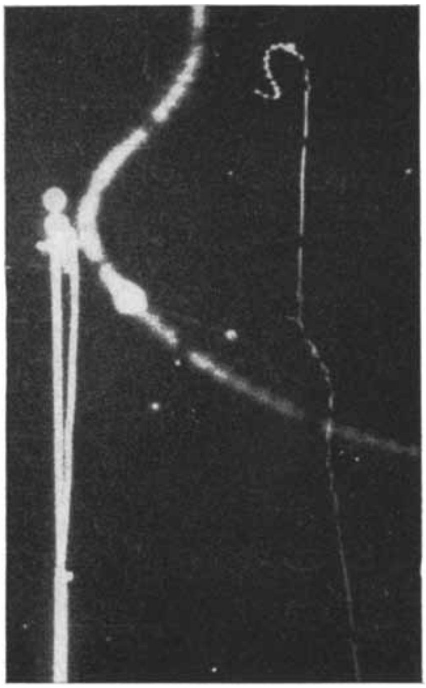
One important finding of this field work was that moths cruising at some distance from the loudspeaker would turn and fly at high speed directly away from it. This happened only if the sound the moths encountered was of low intensity. Moths closer to the loudspeaker could be induced to flee only if the signal was made weaker. Moths at about the height of the loudspeaker flew away in the horizontal plane; those above the loudspeaker were observed to turn directly upward



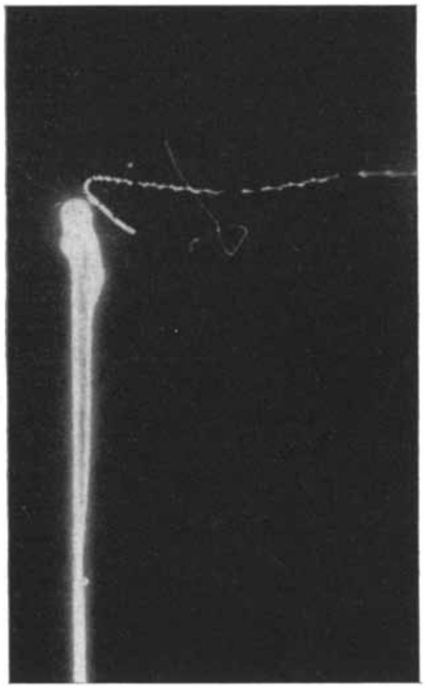
CHANGES ARE REPORTED by moth's tympanic nerve to the oscilloscope as pulses used to simulate bat cries gain intensity. Pulses (*lower trace in each frame*) were at five decibels (*top frame*), 20 (*middle*) and 35 (*bottom*). An increased number of tall spikes appear as intensity of stimulus rises. The time interval between spikes decreases slightly. Smaller spikes from the less sensitive nerve fiber appear at the higher intensities, and the higher the intensity of the stimulus, the sooner (*left on horizontal axis*) the first spike appears.



POWER DIVE is taken by moth on hearing simulated bat cry from loudspeaker mounted on thin tower (*left of moth's flight path*).



PASSIVE DROP was executed by another moth, which simply folded its wings. Blur at left and dots were made by other insects.

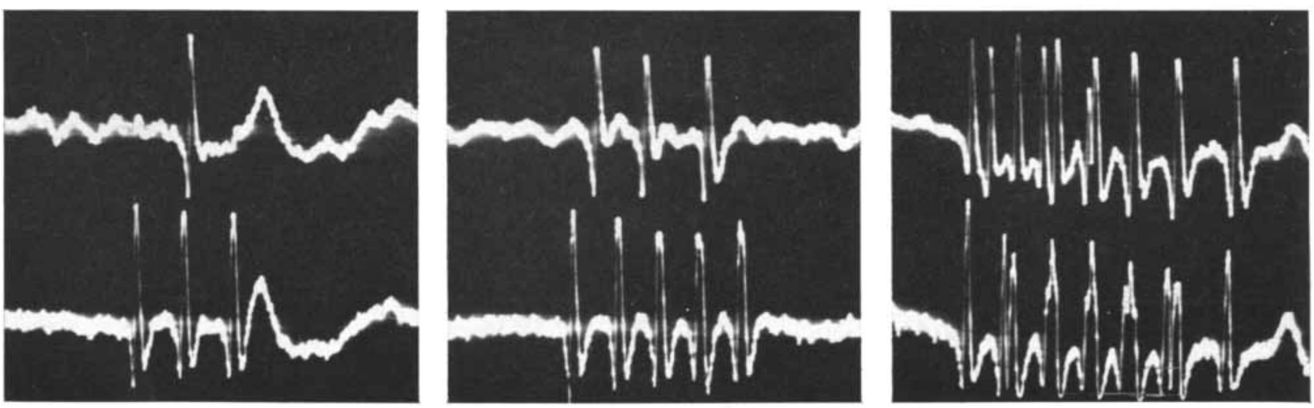


TURNING AWAY, an evasive action involving directional change, is illustrated. These streak photographs were made by author.

or at other sharp angles. To make such directional responses with only four sensory cells is quite a feat. A horizontal response could be explained on the basis that one ear of the moth detected the sound a bit earlier than the other. It is harder to account for a vertical response, although experiments I shall describe provide a hint.

Our second series of field experiments was conducted in another outdoor laboratory—my backyard. They were designed to determine which of the criteria of intensity encoded in the pattern of *A*-fiber spikes play an important part in determining evasive behavior. The percentage of moths showing "no reaction," "diving," "looping" and "turning away" was noted when a 50-kilocycle signal was pulsed at different rates and when it was produced as a continuous tone. The continuous tone delivers more *A* impulses in a given fraction of a second and therefore should be a more effective stimulus if the number of *A* impulses is important. On the other hand, because the *A* cells, like many other sensory cells, become progressively less sensitive with continued stimulation, the interspike interval lengthens rapidly as continuous-tone stimulation proceeds. When the sound is pulsed, the interspike interval remains short because the *A* cells have had time to regain their sensitivity during the brief "off" periods. If the spike-generation time—which is associated with difference in the time at which the *A* spike arrives at the nerve centers for each ear—plays an important part in evasive behavior, then continuous tones should be less effective. The difference in arrival time would be detected only once at the beginning of the stimulus; with pulsed sound it would be reiterated with each pulse.

The second series of experiments occupied many lovely but mosquito-ridden summer nights in my garden and provided many thousands of observations. Tabulation of the figures showed that continuous ultrasonic tones were much less effective in producing evasive



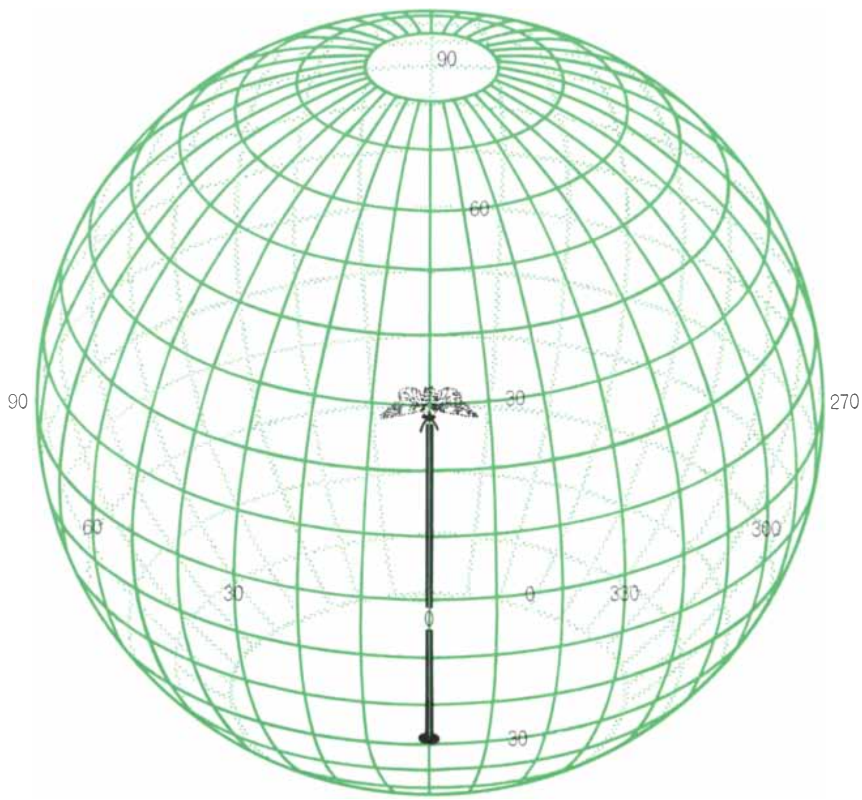
RESPONSE BY BOTH EARS of a moth to an approaching bat was recorded on the oscilloscope and photographed by the author. In trace at left the tympanic nerve from one ear transmits only one spike (*upper curve*) while the nerve from the other ear sends three. As the bat advances, the ratio becomes three to five (*middle*), then 10 to 10 (*right*), suggesting that the bat has flown overhead.

behavior than pulses. The number of nonreacting moths increased threefold, diving occurred only at higher sound intensities and turning away was essentially absent. Only looping seemed to increase slightly.

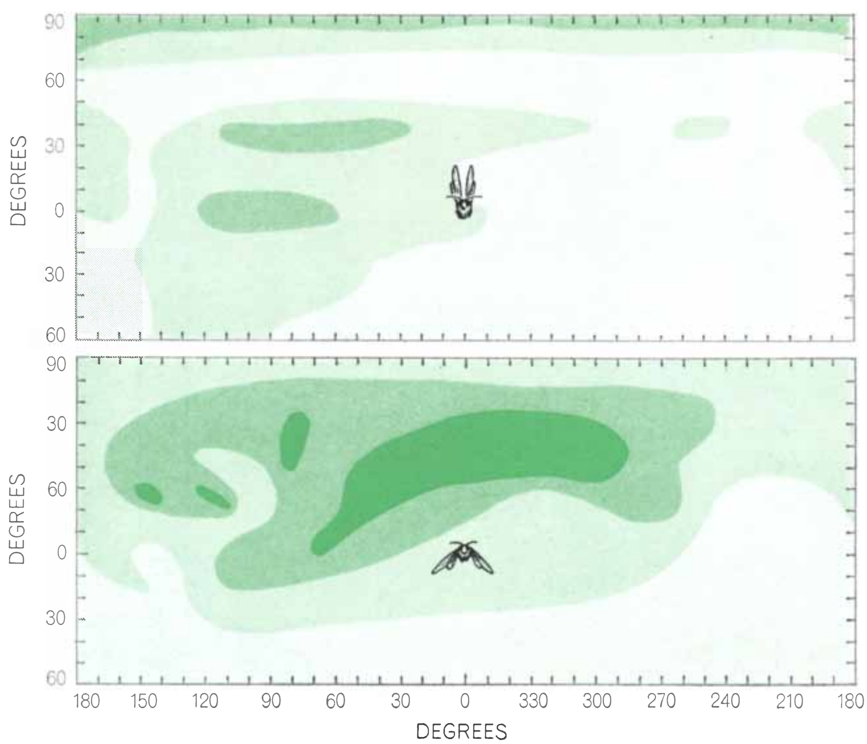
Ultrasound pulsed between 10 and 30 times a second proved to be more effective than ultrasound pulsed at higher or lower rates. This suggests that diving, and possibly other forms of nondirectional evasive behavior, are triggered in the moth's central nervous system not so much by the number of *A* impulses delivered over a given period as by short intervals (less than 2.5 milliseconds) between consecutive *A* impulses. Turning away from the sound source when it is operating at low intensity levels seems to be set off by the reiterated difference in arrival time of the first *A* impulse in the right and left tympanic nerves.

These conclusions were broad but left unanswered the question: How can a moth equipped only with four *A* cells orient itself with respect to a sound source in planes that are both vertical and horizontal to its body axis? The search for an answer was undertaken by Roger Payne of Tufts University, assisted by Joshua Wallman, a Harvard undergraduate. They set out to plot the directional capacities of the tympanic organ by moving a loudspeaker at various angles with respect to a captive moth's body axis and registering (through the A_1 fiber) the organ's relative sensitivity to ultrasonic pulses coming from various directions. They took precautions to control acoustic shadows and reflections by mounting the moth and the recording electrodes on a thin steel tower in the center of an echo-free chamber; the effect of the moth's wings on the reception of sound was tested by systematically changing their position during the course of many experiments. A small loudspeaker emitted ultrasonic pulses 10 times a second at a distance of one meter. These sounds were presented to the moths from 36 latitude lines 10 degrees apart.

The response of the *A* fibers to the ultrasonic pulses was continuously recorded as the loudspeaker was moved. At the same time the intensity of ultrasound emitted by the loudspeaker was regulated so that at any angle it gave rise to the same response. Thus the intensity of the sound pulses was a measure of the moth's acoustic sensitivity. A pen recorder continuously graphed the changing intensity of the ultrasonic pulses against the angle from which



SPHERE OF SENSITIVITY, the range in which a moth with wings in a given position can hear ultrasound coming from various angles, was the subject of a study by Roger Payne of Tufts University and Joshua Wallman, a Harvard undergraduate. Moths with wings in given positions were mounted on a tower in an echo-free chamber. Data were compiled on the moths' sensitivity to ultrasound presented from 36 latitude lines 10 degrees apart.



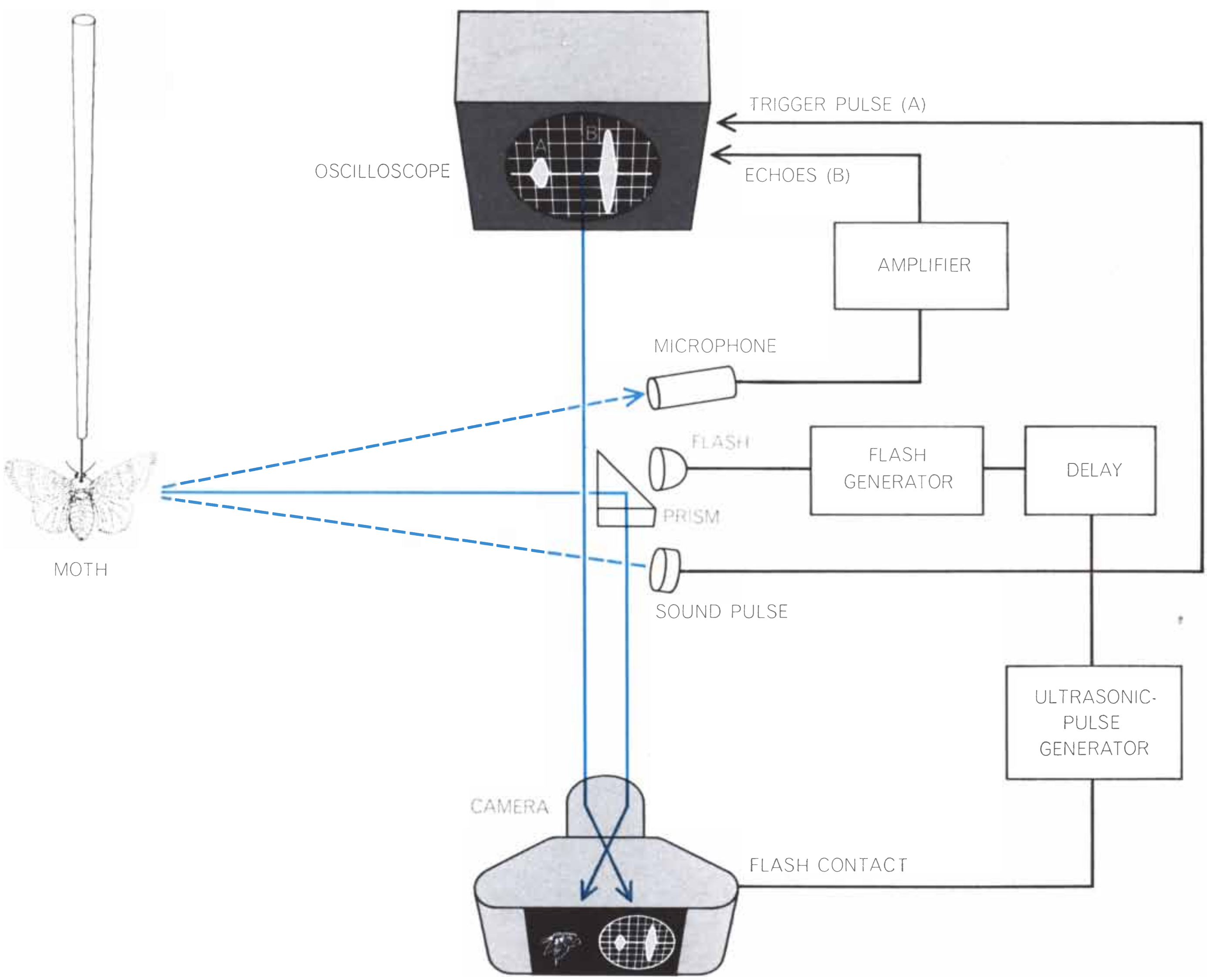
MERCATORIAL PROJECTIONS represent auditory environment of a moth with wings at end of upstroke (*top*) and near end of downstroke (*bottom*). Vertical scale shows rotation of loudspeaker around moth's body in vertical plane; horizontal scale shows rotation in horizontal plane. At top the loudspeaker is above moth; at far right and left, behind it. In Mercatorial projections, distortions are greatest at poles. The lighter the shading at a given angle of incidence, the more sensitive the moth to sound from that angle.

they were presented to the moth. Each chart provided a profile of sensitivity in a certain plane, and the data from it were assembled with those from others to provide a "sphere of sensitivity" for the moth at a given wing position.

This ingenious method made it possible to assemble a large amount of data in a short time. In the case of one moth it was possible to obtain the data for nine spheres of sensitivity (about 5,000 readings), each at a different wing position, before the tympanic nerve of the moth finally stopped transmitting impulses. Two of these spheres, taken from one moth at different wing positions, are presented as Mercatorial projections in the bottom illustration on the preceding page.

It is likely that much of the information contained in the fine detail of such projections is disregarded by a moth flapping its way through the night. Certain general patterns do seem related, however, to the moth's ability to escape a marauding bat. For instance, when the moth's wings are in the upper half of their beat, its acoustic sensitivity is 100 times less at a given point on its side facing away from the source of the sound than at the corresponding point on the side facing toward the source. When flight movements bring the wings below the horizontal plane, sound coming from each side above the moth is in acoustic shadow, and the left-right acoustic asymmetry largely disappears. Moths commonly flap their wings from 30 to 40 times a second. Therefore left-right acoustic asymmetry must alternate with up-down asymmetry at this frequency. A left-right difference in the *A*-fiber discharge when the wings are up might give the moth a rough horizontal bearing on the position of a bat with respect to its own line of flight. The absence of a left-right difference and the presence of a similar fluctuation in both left and right tympanic nerves at wingbeat frequency might inform the moth that the bat was above it. If neither variation occurred at the regular wingbeat frequency, it would mean that the bat was below or behind the moth.

This analysis uses terms of precise directionality that idealize the natural situation. A moth certainly does not zoom along on an even keel and a straight course like an airliner. Its flapping progress—even when no threat is imminent—is marked by minor yawing and pitching; its overall course is rare-

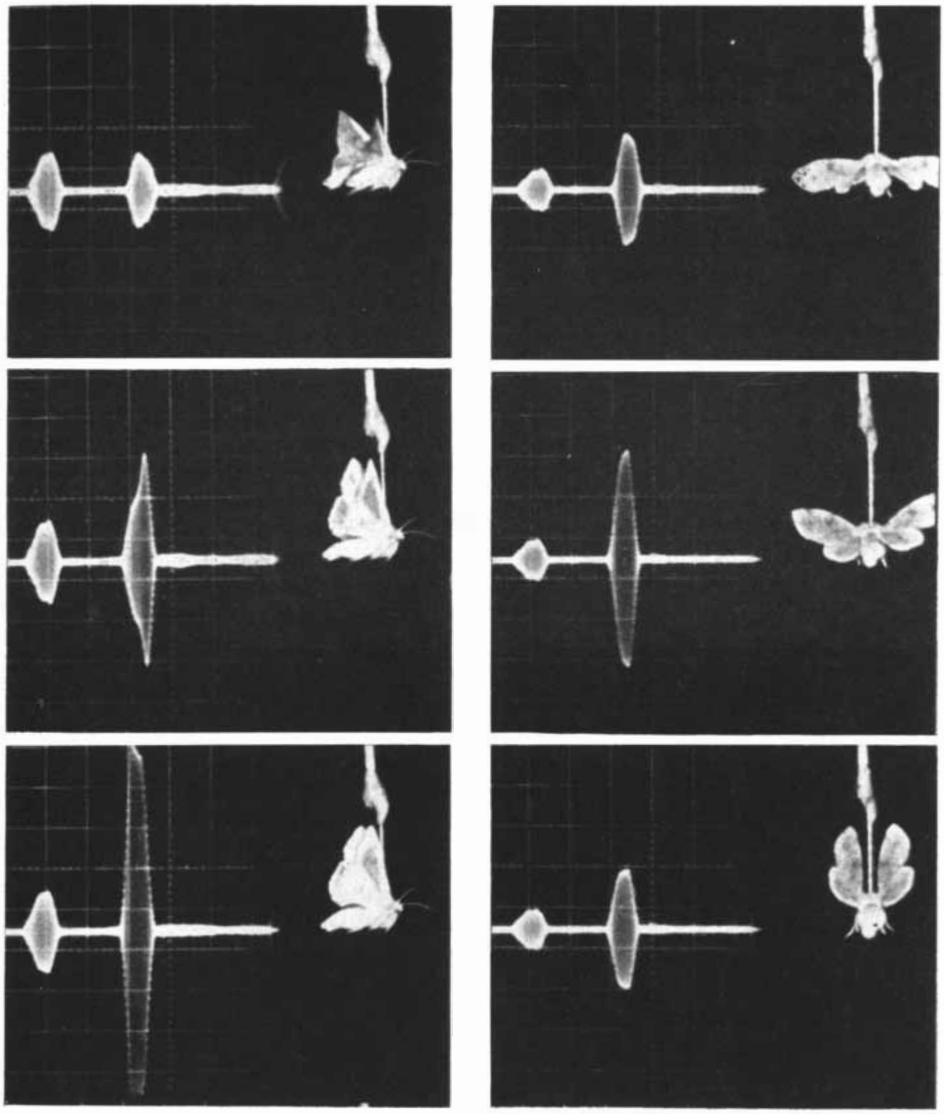


ARTIFICIAL BAT, the electronic device depicted schematically at right, was built by the author to determine at what position with respect to a bat a moth casts its greatest echo. As a moth supported by a wire flapped its wings in stationary flight, a film was made by means of a prism of its motions and of an oscilloscope that showed the pulse generated by the loudspeaker and the echo picked up by the microphone. Each frame of film thus resembled the composite picture of moth and two pulses shown inverted at bottom.

ly straight and commonly consists of large loops and figure eights. Even so, the localization experiments of Payne and Wallman suggest the ways in which a moth receives information that enables it to orient itself in three dimensions with respect to the source of an ultrasonic pulse.

The ability of a moth to perceive and react to a bat is not greatly superior or inferior to the ability of a bat to perceive and react to a moth. Proof of this lies in the evolutionary equality of their natural contest and in the observation of a number of bat-moth confrontations. Donald R. Griffin of Harvard University and Frederic Webster of the Sensory Systems Laboratories have studied in detail the almost unbelievable ability of bats to locate, track and intercept small flying targets, all on the basis of a string of echoes thrown back from ultrasonic cries. Speaking acoustically, what does a moth "look like" to a bat? Does the prey cast different echoes under different circumstances?

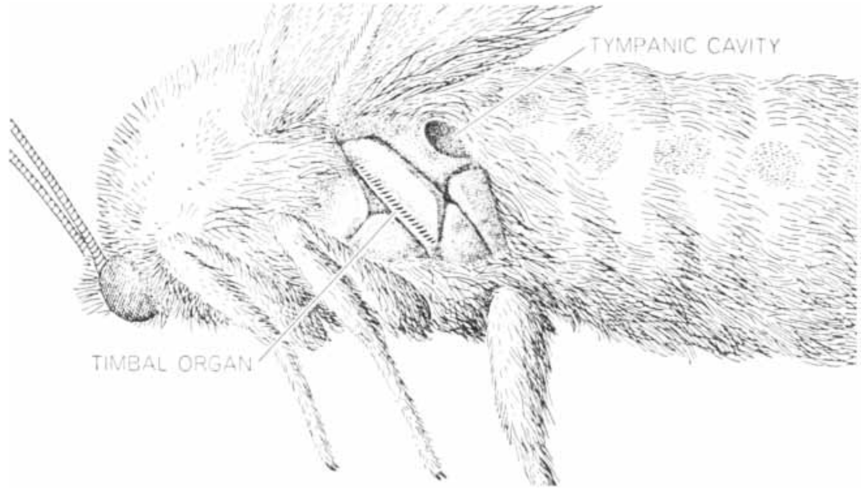
To answer this question I set up a crude artificial bat to pick up echoes from a live moth. The moth was attached to a wire support and induced to flap its wings in stationary flight. A movie camera was pointed at a prism so that half of each frame of film showed an image of the moth and the other half the screen of an oscilloscope. Mounted closely around the prism and directed at the moth from one meter away were a stroboscopic-flash lamp, an ultrasonic loudspeaker and a microphone. Each time the camera shutter opened and exposed a frame of film a short ultrasonic pulse was sent out by the loudspeaker and the oscilloscope began its sweep. The flash lamp was controlled through a delay circuit to go off the instant the ultrasonic pulse hit the moth, whose visible attitude was thereby frozen on the film. Meanwhile the echo thrown back by the moth while it was in this attitude was picked up by the microphone and finally displayed as a pulse of a certain height on the oscilloscope. All this took place before the camera shutter closed and the film moved on to the next frame. Thus each frame shows the optical and acoustic profiles of the moth from approximately the same angle and at the same instant of its flight. The camera was run at speeds close to the wingbeat frequency of the moth, so that the resulting film presents a regular series of wing positions and the echoes cast by them.



COMPOSITE PHOTOGRAPHS each show an artificial bat's cry (*left*) and the echo thrown back (*middle*) by a moth (*right*). The series of photographs at left is of a moth in stationary flight at right angles to the artificial bat. Those at right are of a moth oriented in flight parallel to the bat. The echo produced in the series of photographs at left is much the larger.

Films made of the same moth flying at different angles to the camera and the sound source show that by far the strongest echo is returned when the moth's wings are at right angles to the recording array [*see illustrations at left*]. The echo from a moth with its wings in this position is perhaps 100 times stronger than one from a moth with its wings at other angles. Apparently if a bat and a moth were flying horizontal courses at the same altitude, the moth would be in greatest danger of detection if it crossed the path of the approaching bat at right angles. From the bat's viewpoint at this instant the moth must appear to flicker acoustically at its wingbeat frequency. Since the rate at which the bat emits its ultrasonic cries is independent of the moth's wingbeat frequency, the actual sequence of echoes the bat receives must be complicated by the interaction of the two frequencies. Perhaps this enables the bat to discriminate a flapping target, likely to be prey, from inert objects floating in its acoustic field.

The moth has one advantage over the bat: it can detect the bat at a greater range than the bat can detect it. The bat, however, has the advantage of greater speed. This creates a nice problem for a moth that has picked up a bat's cries. If a moth immediately turns and flies directly away from a source of ultrasound, it has a good chance of disappearing from the sonar system of a still-distant bat. If the bat has also detected the moth, and is near enough to receive a continuous signal from its target, turning away on a straight course is a bad tactic because the moth is not likely to outdistance its pursuer. It is then to the moth's advantage to



NOISEMAKING ORGAN possessed by many moths of the family Arctiidae and of other families is a row of fine parallel ridges of cuticle that bend and unbend when a leg muscle contracts and relaxes. This produces a rapid sequence of high-pitched clicks.

go into tight turns, loops and dives, some of which may even take it toward the bat.

In this contest of hide-and-seek it seems much to a moth's advantage to remain as quiet as possible. The sensitive ears of a bat would soon locate a noisy target. It is therefore surprising to find that many members of the moth family Arctiidae (which includes the moths whose caterpillars are known as woolly bears) are capable of generating trains of ultrasonic clicks. David Blest and David Pye of University College London have demonstrated the working of the organ that arctiids use for this purpose.

In noisemaking arctiids the basal joint of the third pair of legs (which roughly corresponds to the hip) bulges outward and overlies an air-filled cavity. The stiff cuticle of this region has a series of fine parallel ridges [*see illustration above*]. Each ridge serves as a timbal that works rather like the familiar toy incorporating a thin strip of spring steel that clicks when it is pressed by the thumb. When one of the moth's leg muscles contracts and relaxes in rapid sequence, it bends and unbends the overlying cuticle, causing the row of timbals to produce rapid sequences of high-pitched clicks. Blest and Pye found that such moths would click when they were handled or poked, that the clicks occurred in short bursts of 1,000 or more per second and that each click contained ultrasonic frequencies within the range of hearing of bats.

My colleagues and I found that certain arctiids common in New England could also be induced to click if they were exposed to a string of ultrasonic pulses while they were suspended in stationary flight. In free flight these moths showed the evasive tactics I have already described. The clicking seems almost equivalent to telling the bat, "Here I am, come and get me." Since such altruism is not characteristic of the relation between predators and prey, there must be another answer.

Dorothy C. Dunning, a graduate student at Tufts, is at present trying to find it. She has already shown that partly tamed bats, trained to catch mealworms that are tossed into the air by a mechanical device, will commonly swerve away from their target if they hear tape-recorded arctiid clicks just before the moment of contact. Other ultrasounds, such as tape-recorded bat cries and "white" noise (noise of all frequencies), have relatively little effect on the bats' feeding behavior; the tossed mealworms are caught in midair and eaten. Thus the clicks made by arctiids seem to be heeded by bats as a warning rather than as an invitation. But a warning against what?

One of the pleasant things about scientific investigation is that the last logbook entry always ends with a question. In fact, the questions proliferate more rapidly than the answers and often carry one along unexpected paths. I suggested at the beginning of this article that it is my intention to trace the nervous mechanisms involved in the evasive behavior of moths. By defining the information conveyed by the acoustic cells I have only solved the least complex half of that broad problem. As I embark on the second half of the investigation, I hope it will lead up as many diverting side alleys as the study of the moth's acoustic system has.

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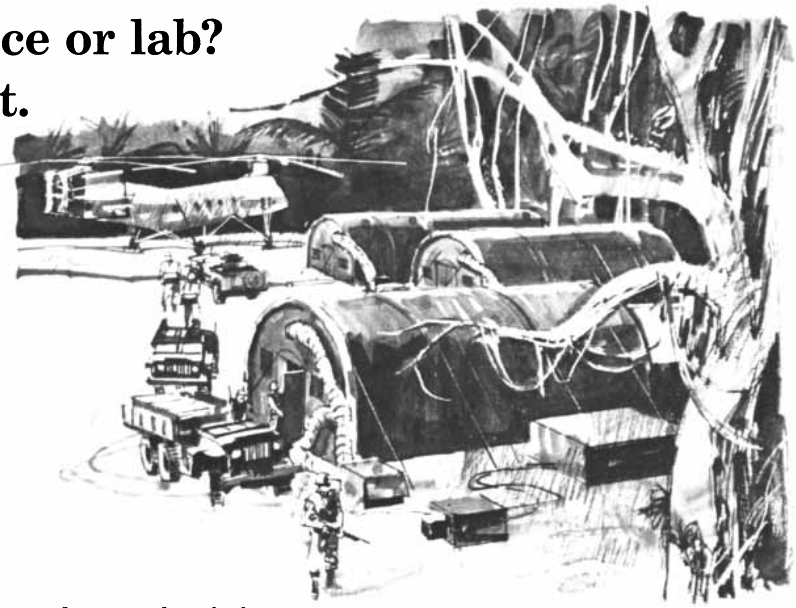

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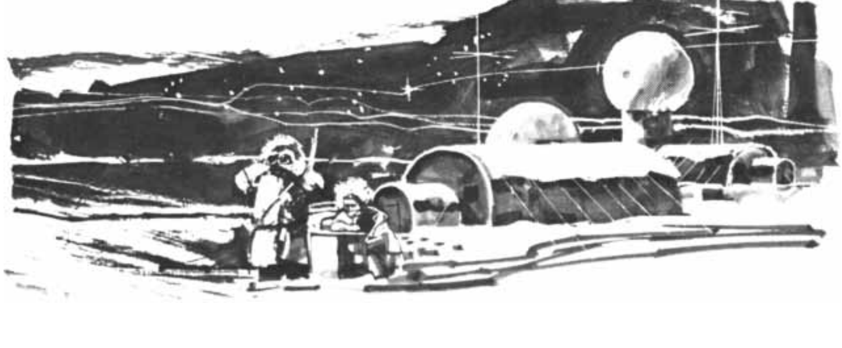

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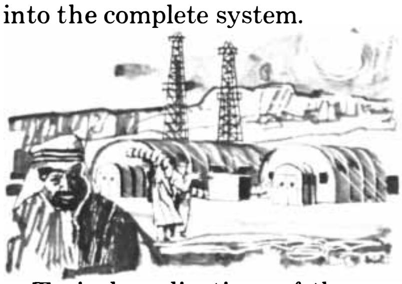

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THE DISCOVERY OF ICARUS

A chunk of rock less than a mile in diameter, Icarus comes closer to the sun and the earth than any other asteroid whose orbit has been accurately computed. It should miss us by four million miles in 1968

by Robert S. Richardson

The probability that the earth will collide with an asteroid is extremely small, but not so small that it can be totally ignored. Asteroids are irregularly shaped bodies, also called minor planets or planetoids, that range in diameter from slightly less than a mile up to about 500 miles. The *Ephemerides of Minor Planets for 1965* lists 1,651 that have been assigned a number and 1,520 with proper names. Practically all of these objects travel uneventfully around the sun in orbits lying between those of Mars and Jupiter. About a dozen, however, are known to move in elongated, comet-like orbits that periodically bring them near the orbit of the earth. We are aware of these close-approaching asteroids only through the accident of discovery. No one knows how many objects ranging in size from a few miles in diameter downward may pass near the earth each year without being noticed.

I shall recount the discovery of an asteroid about six-tenths of a mile in diameter that comes closer to the sun and the earth than any other planetary object whose orbit has been well established. It was named Icarus, after the adventuresome youth who flew too close to the sun with wings made of wax and feathers. Asteroid Icarus passes within 17 million miles of the sun, and when it was discovered accidentally in 1949, it had just passed within four million miles of the earth.

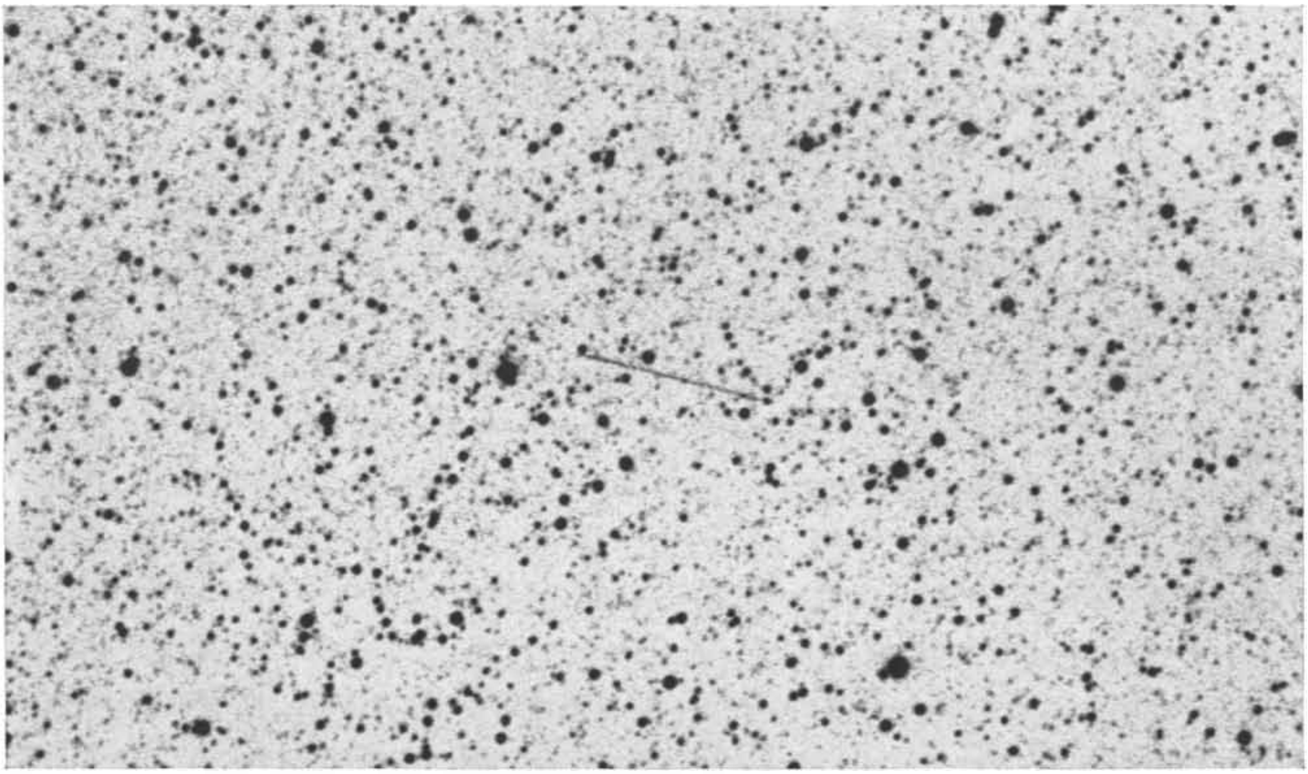
The story of Icarus' discovery illustrates how easy it is to be wholly unaware of a massive body hurtling past the earth at high speed and how difficult it can be to obtain enough observations to calculate a reliable orbit. For lack of such observations three asteroids that came even closer to the earth than Icarus—Apollo, Adonis and Hermes—have not been seen again since their original close approach. In 1932 Apollo passed within two million miles of the earth; in 1936 Adonis came within slightly less than a million miles; in 1937 Hermes came within 485,000 miles, or about twice the distance from the earth to the moon, a record that still stands today. Adonis was lost in spite of being carefully tracked for two months in 1936. In June, 1943, when it was supposed to make another close approach, I failed to find it even though I made an extensive search with the 100-inch telescope on Mount Wilson. Apollo, Adonis and Hermes are estimated to be about a mile in diameter and thus are probably a trifle larger than Icarus. These estimates are quite uncertain because they are not derived from direct measurements but depend on the amount of light assumed to be reflected from the surface of the asteroid.

In 1968 Icarus will again pass within four million miles of the earth. The prediction can be made with confidence because it is based on observations obtained in 1949, 1950, 1952, 1953, 1954 and 1957. These have been combined in a definitive orbit prepared under the supervision of Samuel Herrick of the University of California at Los Angeles; it includes the perturbing effects of all the planets except Pluto. A change of only a few degrees in the position of the descending node of Icarus' orbit, the point at which the asteroid crosses the plane of the earth's orbit from north to south, would make it possible for Icarus and the earth to be at the same place at the same time.

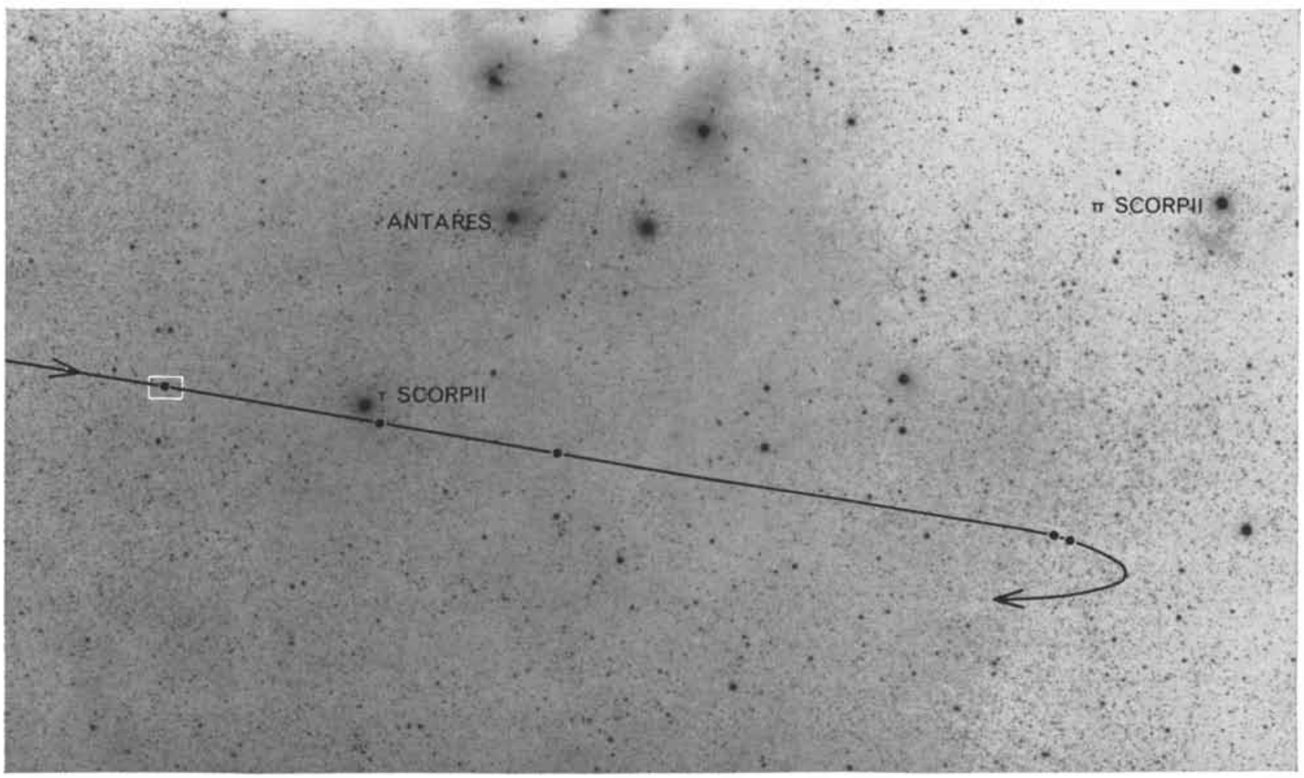
There is no unequivocal record that the earth has ever been hit by a body the size of Icarus or larger. It is a matter of definition whether certain large craters, such as Meteor Crater in Arizona, were produced by meteorites—the term reserved for meteoroids that strike the earth—or by small asteroids. A meteoroid can be defined operationally as an object too small to be observed in space by reflected light even with the most powerful telescope; it becomes visible only when it penetrates the earth's atmosphere and leaves a glowing trail. It has recently been estimated that an excavation the size of Meteor Crater, which is 4,000 feet across and 570 feet deep, could be produced by a 20-megaton nuclear explosion set off a few hundred feet below the earth's surface. The force of such an explosion could be duplicated by a meteoroid weighing about 180,000 tons, which, if it were made chiefly of iron, could be contained within a sphere only 110 feet in diameter. Such an object would be much smaller than any of the asteroids whose orbits are known.

Even if close surveillance revealed that a collision between the earth and Icarus were imminent sometime in the future, what could be done about it? Conceivably one might try to destroy it by intercepting it with a nuclear-armed space vehicle. A cleverer idea would be to land a rocket engine on it capable of pushing it slightly off course. Either measure would provide a challenging assignment for space technologists.

The remote possibility of collision is not the only reason for keeping Icarus under close surveillance; the asteroid could provide an important test of the general theory of relativity. One prediction of the theory is that the elliptical orbit of a body revolving around the sun undergoes a slow change in orientation: the point of perihelion and with it the major axis of the ellipse rotate slowly in the direction of the body's motion. The major axis of Mer-



DISCOVERY PHOTOGRAPH made by Walter Baade on June 26, 1949, shows the asteroid later named Icarus as a faint streak in a rich field of stars. The photograph, a 60-minute exposure, was among the first made with the then recently completed 48-inch Schmidt telescope on Palomar Mountain. This is an enlarged negative print of a section that measures about 1/2 by 3/4 inch on the original 14-by-14-inch Schmidt plate. Icarus is moving to the right. It was then about 22 million miles away, having passed within four million miles of the earth on June 15. The path of Icarus at the time of its discovery is traced on a wide-angle view of the sky below.



PATH OF ICARUS took it through the region of Scorpius. The three widely spaced dots show the position of Icarus on June 26, 28 and 30, when it was first photographed; it was moving southwest in rapid retrograde motion with respect to the background stars. The next two dots show its position on July 12 and 13, when it was photographed again. The rectangle outlines the region shown in the photograph at the top of the page. This wide-field picture was made by F. E. Ross of the Yerkes Observatory.

cury's orbit is rotating eastward at the rate of nine minutes 34 seconds of arc per century. Most of this displacement is caused by the gravitational effects of Venus and other planets, but it has been known for a long time that the total is 43 seconds more than can be accounted for by the Newtonian theory of gravitation alone. The discrepancy between theory and observation was finally explained by the general theory of relativity, which predicted an advance of 43 seconds per century in the perihelion of Mercury, in exact agreement with observation. The relativistic effect is more pronounced the smaller the orbit, and the greater its elongation, or degree of eccentricity. Until 1949 Mercury was the only body that furnished a definite test of the theory. Because the orbit of Icarus is more eccentric than that of Mercury it should eventually provide an even better test.

One asteroid, Eros, has already earned a place of honor in the history of astronomy by serving as a yardstick for measuring the size of the solar system. At the time of its discovery in 1898 Eros was the first asteroid known to pass inside the orbit of Mars. On the most favorable occasions it comes within 14 million miles of the earth and is large enough to be easily photographed. In 1931 Eros came within 16.2 million miles of the earth and in 1938 within 20 million miles.

The fundamental measurement for scaling the solar system is the "astronomical unit," the mean distance from the center of the earth to the center of the sun. The sun itself is too distant and too bright for accurate trigonometric measurement from two widely separated stations on the earth's surface. For a long time Venus and Mars were the only bodies suitable for such measurements, but even our nearest neighbor, Venus, does not come closer than 26 million miles. Eros comes so close, however, that it shows an easily measured displacement with respect to the stars when it is photographed simultaneously from observatories in the Northern and Southern hemispheres. Moreover, positions of Eros are accurately defined because its image on photographic plates is pointlike, resembling a star, rather than disklike, which is the case with planets. At these close approaches the motion of Eros is strongly perturbed by the earth. From an analysis of these perturbations it is possible to derive a highly accurate value of the ratio of the mass of the earth to the mass of the sun, as well as of the mass of the moon to that of the earth. These ratios provided the most accurate determination of the astronomical unit until they were superseded in recent years by radio-echo measurements that directly determine the distance from the earth to the nearby planets.

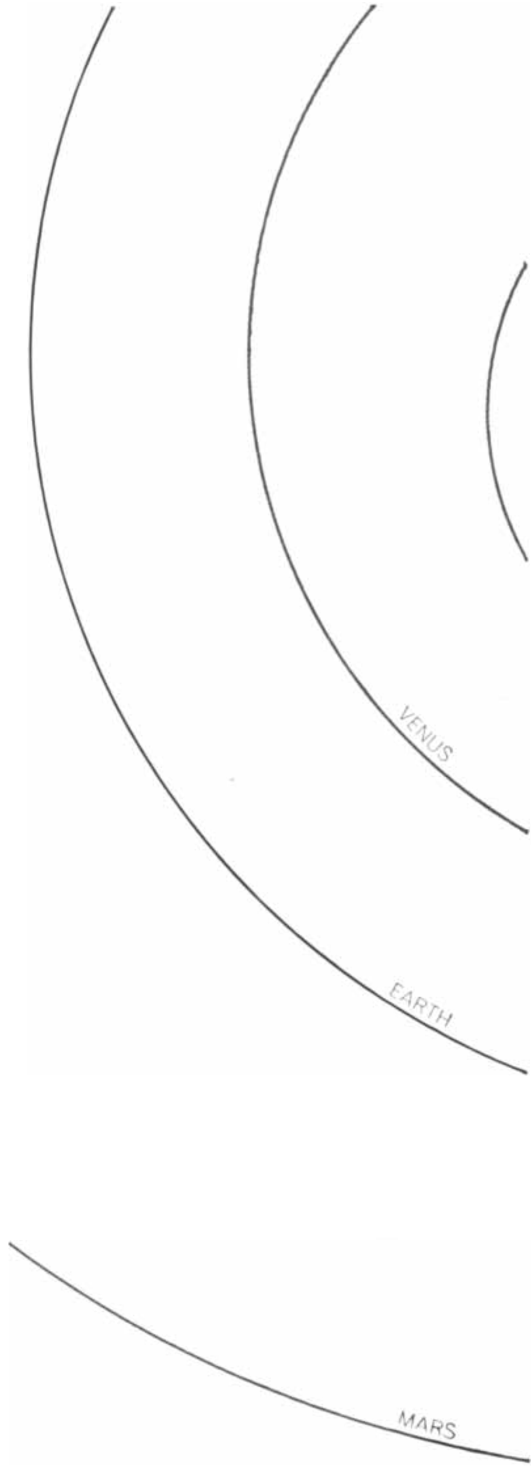
The first asteroid was discovered by Father Giuseppe Piazzi of the astronomical observatory at Palermo in Sicily, who was engaged in making an extensive star catalogue. On January 1, 1801—the first night of the 19th century—he observed through his telescope a starlike object that he had difficulty identifying with stars shown in previous catalogues. The next night the object had moved, proving that it was not a star but an object inside the solar system.

For the first two weeks the object moved slowly eastward, then came to a stop and began traveling in a retrograde, or westerly, direction. It was these loops that had led the early astronomers to believe the planets moved in complex epicycles as they revolved around the earth. Piazzi was of course aware that the back-and-forth motion was simply an illusion due to the fact that the earth is also revolving around the sun, thus regularly overtaking planets farther away from the sun and being overtaken by the planets nearer the sun.

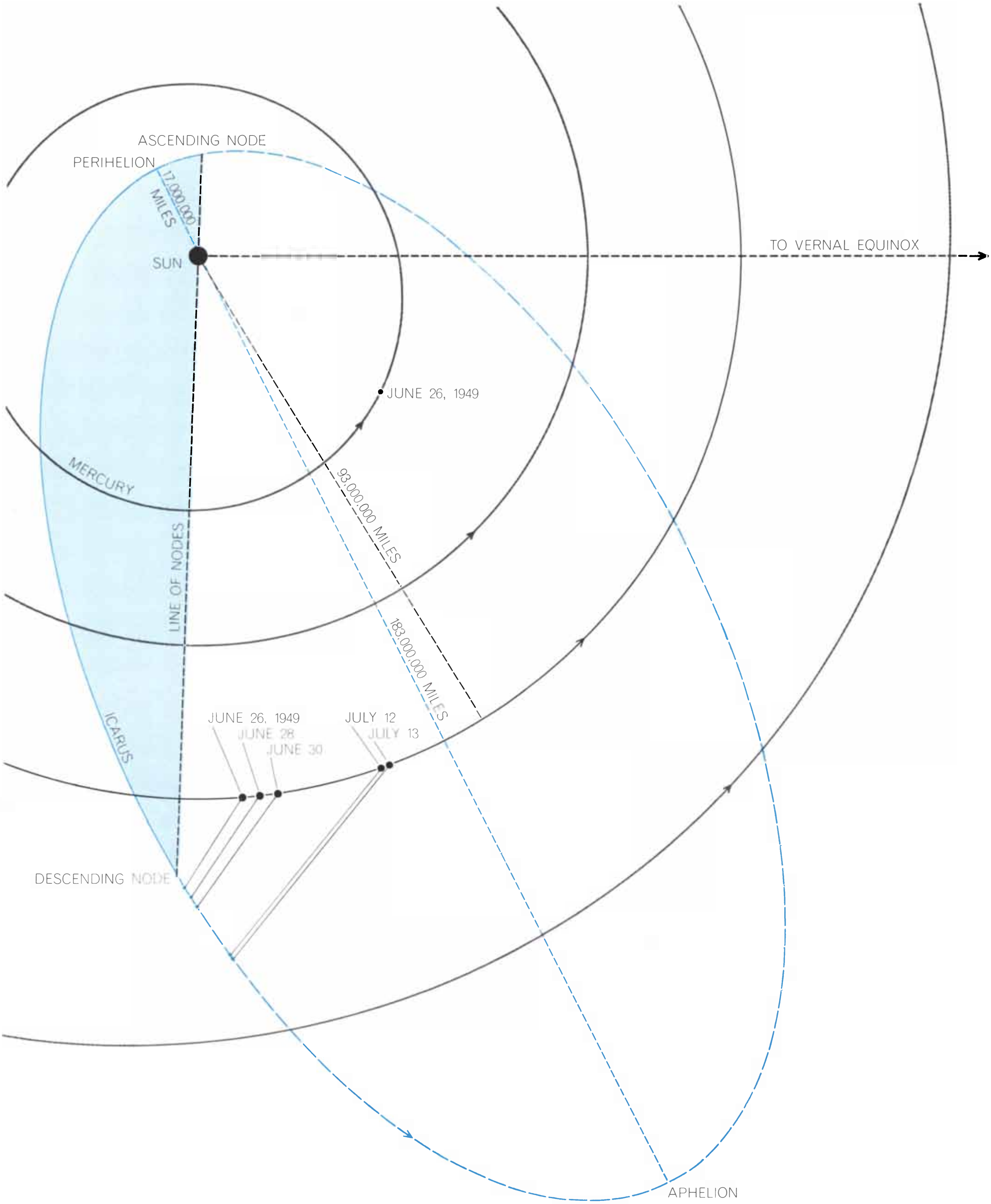
At first Piazzi thought his new object might be a comet, but since it lacked the fuzzy outline characteristic of most comets he concluded that he had discovered a new small planet. He named it Ceres, for the guardian divinity of Sicily. After observing the asteroid for six weeks Piazzi became ill; when he returned to his telescope, Ceres was lost in the glow of the evening sky.

As it happened, the great mathematician Karl Friedrich Gauss had just worked out a simplified method for calculating orbits from only three or four observations. With Piazzi's charts he computed an orbit for Ceres, which enabled him to tell astronomers where to look for the planet. It was picked up without difficulty on December 31, 1801, exactly a year after it was first seen, within the apparent diameter of the moon of its predicted position. According to Gauss's calculations the orbit of Ceres was located between the orbits of Mars and Jupiter.

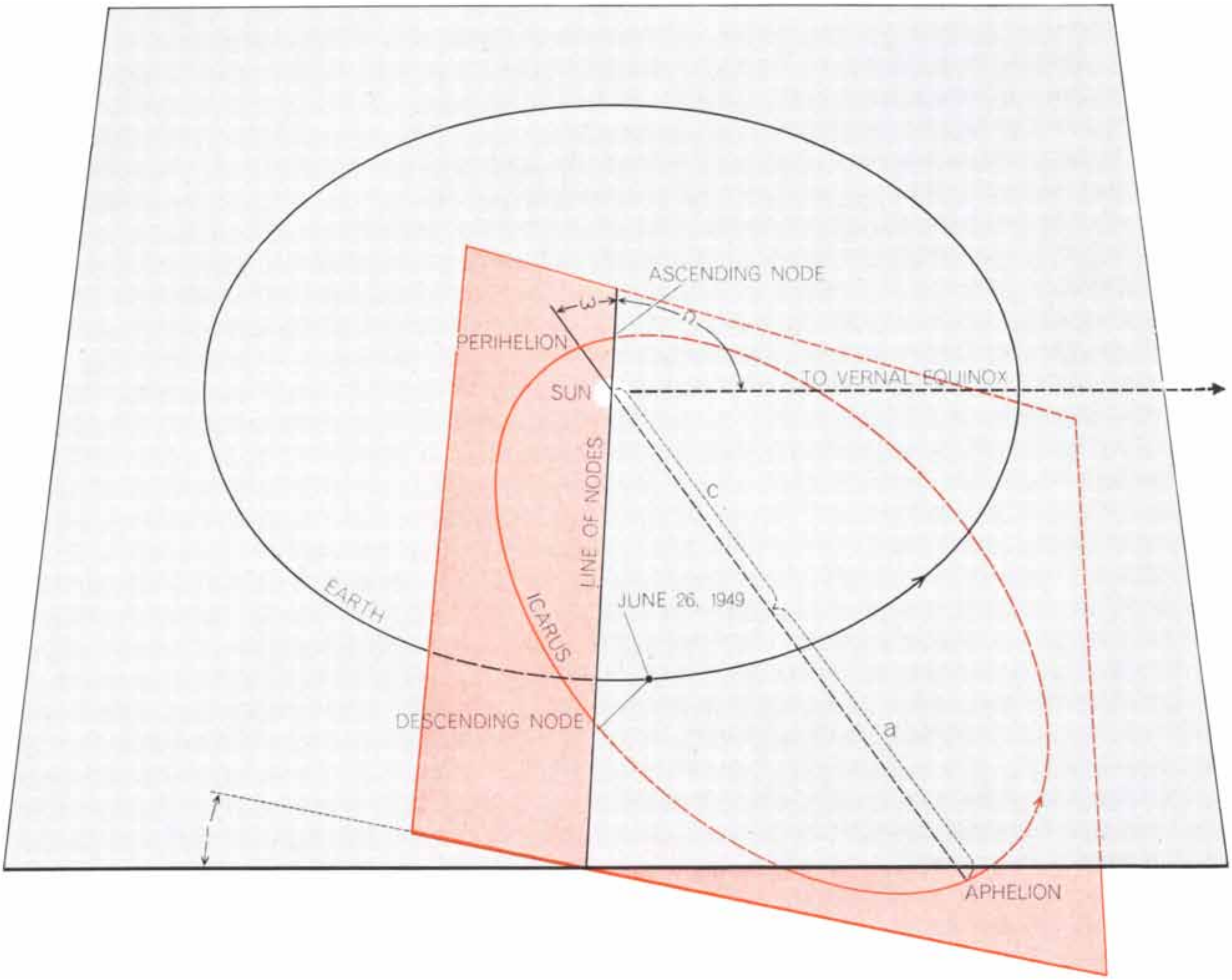
By coincidence an association of astronomers had just been formed for the purpose of looking for a small planet in just that region when they received word that Ceres had been discovered.



ORBIT OF ICARUS passes closer to the sun than that of any other known asteroid. At perihelion, or point of closest approach, Icarus is 17 million miles from the sun, compared with 28.6 million miles for Mercury,



the innermost planet. At aphelion Icarus is 183 million miles from the sun. The orbit of Icarus is tilted 23 degrees to the plane of the earth's orbit; the line of nodes shows where the planes of the two orbits intersect. The part of Icarus' orbit filled in with color is above the plane of the earth's orbit. Although Icarus missed the earth by four million miles in 1949 and should miss by about the same margin in 1968 (*see illustrations on page 111*), only a small shift in its orbit would be needed to send it much closer on subsequent passages. Because it passes near Mercury as well as near the earth its orbit will change significantly with the passage of time.



COMPUTATION OF ASTEROID ORBIT requires the determination of six elements, which can be expressed in a variety of ways. Five elements are needed to describe the size, shape and orientation of the ellipse itself; the sixth gives the asteroid's position at a particular time. The size and shape of the ellipse are given by two elements: the length of the semimajor axis, a, and the eccentricity, e, defined as c/a, where c is the distance from the sun to the center of the ellipse. A third element, i, gives the angle between the plane of the asteroid's orbit and that of the earth's. A fourth element, ☊, is the longitude of the ascending node. It is the angular distance measured eastward in the plane of the earth's orbit, or ecliptic, from the vernal equinox to the point where the asteroid crosses the ecliptic from south to north. A fifth element, ω (small omega), defines how the major axis of the ellipse is oriented in its orbital plane by giving the angle between the ascending node and the perihelion point, measured in the plane of the asteroid's orbit and in the direction of the asteroid's motion. The sixth element is usually given as the time when the asteroid passes perihelion. For Icarus a is 1.0777 astronomical units (100.2 million miles), e is .827, i is 22.979 degrees, ☊ is 87.746 degrees and ω is 30.912 degrees. The time of Icarus' first perihelion passage after its discovery was June 4, 1950.

The large gap between the orbits of Mars and Jupiter had puzzled astronomers since the time of Johannes Kepler early in the 17th century. In 1772 J. D. Titius, a professor at the University of Wittenberg, had published an empirical law of planetary distances that provided for a planet at 2.8 astronomical units; Titius' "law" would probably have been forgotten had it not come to the attention of Johann Bode, editor of the influential *Astronomisches Jahrbuch*. Bode gave it such wide publicity that it became generally known as "Bode's law."

The law can be expressed by adding .4 to the progression 0, .3, .6, 1.2, 2.4, 4.8, 9.6, 19.2 and so on; this yields a sequence in which the first eight numbers are .4, .7, 1.0, 1.6, 2.8, 5.2, 10.0 and 19.6. If these numbers are regarded as astronomical units, the first four and the last three agree quite closely with the positions of Mercury, Venus, the earth, Mars, Jupiter, Saturn and Uranus—the seven planets known at the close of the 18th century. Bode became convinced there must be a planet at the unoccupied distance of 2.8 units. The discovery of Ceres precisely at this distance just 20 years after Uranus had been discovered only .4 astronomical unit away from its predicted position seemed an amazing confirmation of Bode's "law." Faith in the relation was badly shaken in 1846 with the discovery of Neptune, which turned out to be nearly nine astronomical units from its predicted position. The law breaks down completely in the case of Pluto, which is at 39.5 astronomical units rather than the predicted 77.2 units [*see top illustration on page 114*].

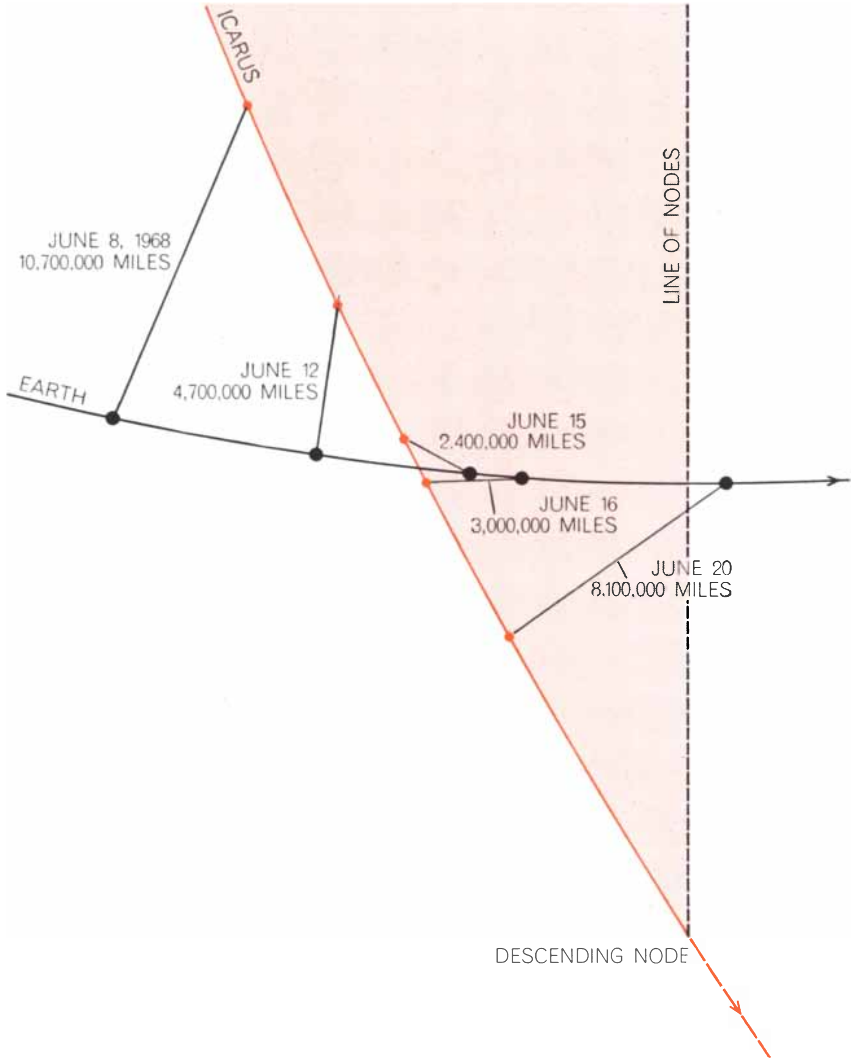
Three more asteroids were discovered in rapid succession: Pallas in 1802, Juno in 1804 and Vesta in 1807. All have orbits quite close to 2.8 astronomical units. The rate of discovery was slow and sporadic until photographic methods of search were instituted in

1891 by Max Wolf of the observatory at Heidelberg. In the 50 years from 1890 to 1940 the number of recognized asteroids increased from fewer than 300 to nearly 1,500.

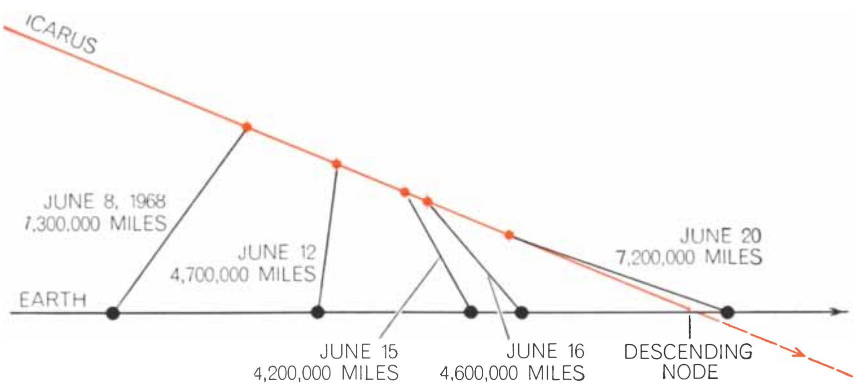
As a result astronomers have become increasingly selective in their search. Today when an astronomer sees on one of his plates an elongated image that is presumably an asteroid, he seldom bothers to pursue it further unless the streak is an exceptionally long one, indicating an object moving close to the earth. It has been estimated that there are 55,000 asteroids bright enough to be photographed with a 100-inch telescope when they are nearest the earth.

We can be reasonably sure that there are no undiscovered asteroids more than a few miles in diameter. Ceres, the first asteroid discovered, is also the largest known, with a diameter of 480 miles. Only it and three others are large enough for their diameters to be determined by direct measurement of their disk. The other three are Pallas (304 miles), Vesta (248 miles) and Juno (118 miles). Curiously Vesta, the third largest in size, is the only asteroid that becomes visible to the unaided eye. Its visibility is attributable to the high reflectivity of its surface.

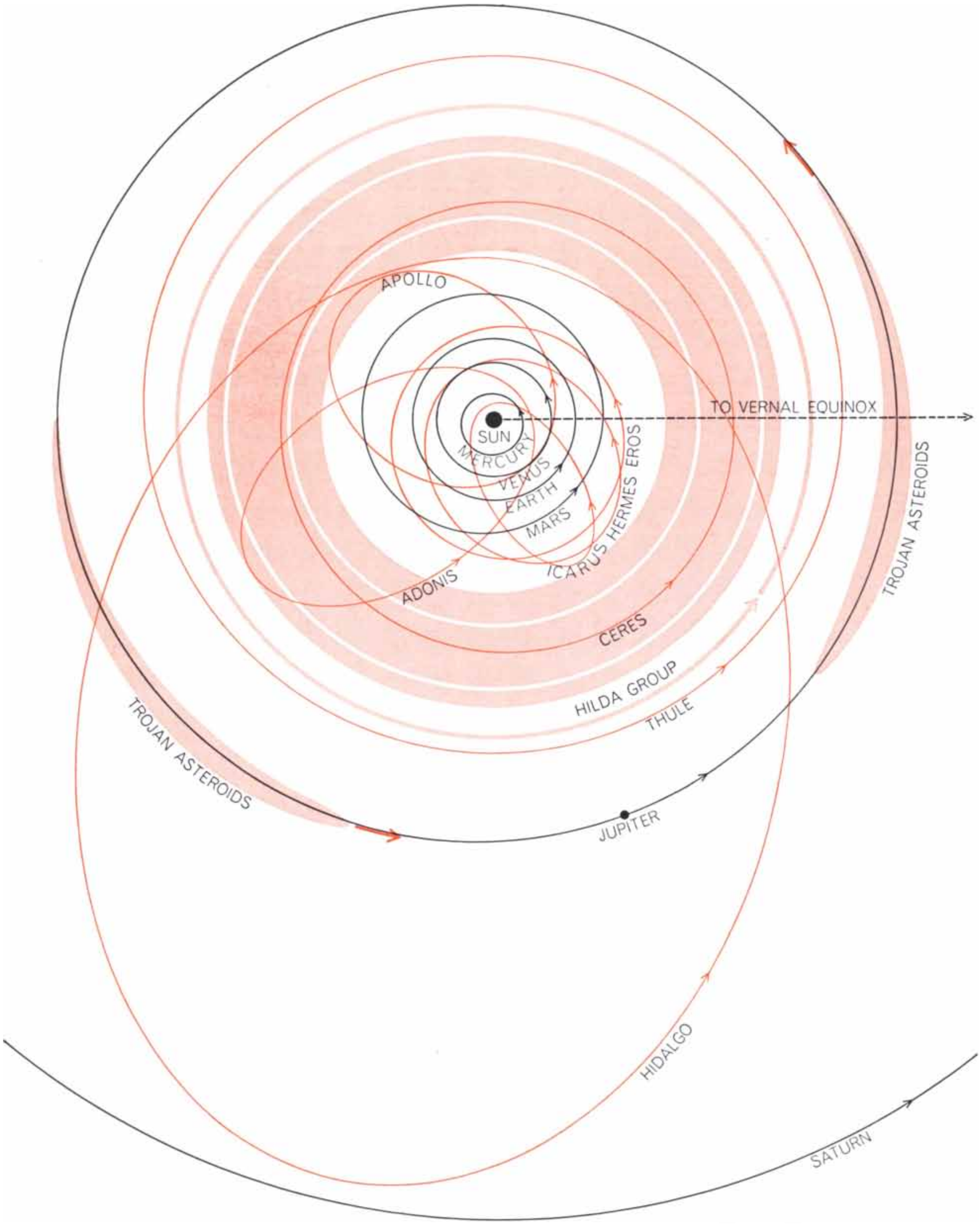
On February 22, 1906, Wolf discovered asteroid 588, later named Achilles; it was the first member of what has since become known as the Trojan group. (In his busy career Wolf discovered 582 asteroids, of which 228 received recognition—a personal record that still stands.) The Trojan asteroids, of which 14 are now recognized, revolve around the sun at about the same distance as Jupiter in approximately the same orbital plane. Nine of them precede Jupiter by about 60 degrees and the other five trail by about 60 degrees. They are of considerable interest in the theory of planetary motions, since they occupy the "Lagrangian points": positions that the French mathematician Joseph Louis Lagrange had predicted more than a century earlier would be stable for secondary bodies moving in the same plane as the primary planet if both bodies were revolving around the sun in circular orbits undisturbed by other planets. Under such ideal conditions if the primary planet and asteroid are 60 degrees apart, they will remain 60 degrees apart. The Trojans only satisfy these conditions approximately; moreover, their motions are disturbed by Saturn. Thus their positions deviate widely from the theoretical 60-degree point [*see illustration on next page*].



NEXT ICARUS-EARTH MEETING will be in June, 1968, when the two bodies will again pass each other at a distance of about four million miles. Here the path of Icarus is shown projected onto the plane of the earth's orbit. The distances refer to this projection and are therefore somewhat less than the actual distances computed in three dimensions. As shown in the projection below, asteroid Icarus will be about 4.2 million miles above and slightly behind the earth on June 15, when the two planetary bodies make their closest approach.



EDGE-ON VIEW during the close approach of 1968 shows the orbits of Icarus and the earth projected onto a plane perpendicular to the line of nodes. Beginning about June 10 Icarus will move into the evening sky and should then remain observable for about two weeks.



ASTEROID PATHS lie predominantly between the orbits of Mars and Jupiter where the first asteroid, Ceres, was found in 1801. The three closely spaced colored bands show the general location of more than 1,500 asteroids discovered since then. The two white separations between bands indicate relatively sparse regions where a resonance is set up between the period of an asteroid and the period of Jupiter, with the result that the asteroid is shifted into a nonresonant orbit. The 14 known Trojan asteroids are remarkable in that they precede and follow Jupiter by about 60 degrees, occupying what are called the Lagrangian points. They oscillate around these points within the two lenticular regions. Hidalgo, discovered by Baade in 1920, travels farther from the sun than any other known asteroid. Apollo, Adonis and Hermes made the closest-known approaches to the earth—within two million miles—but have been lost from sight. Eros helped to refine the value of the astronomical unit, the mean distance from the earth to the sun.

In 1920 the distance record held by the Trojan asteroids was broken when Walter Baade—using the 39-inch reflector of the Hamburg Observatory in Bergedorf, Germany—discovered asteroid 944, later named Hidalgo. Its orbit has a semimajor axis (half the longest dimension of an ellipse) of 5.8 astronomical units, and is so eccentric that at perihelion it comes within two astronomical units of the sun and at aphelion recedes to a distance of 9.6 astronomical units, which is Saturn's mean distance from the sun. The orbit of Hidalgo is inclined to that of the earth by 42.5 degrees, which is exceeded only by that of asteroid 1580 (Betulia), which has an inclination of 52.03 degrees.

Although Baade was only casually interested in asteroids, it was he who happened to discover Icarus, the asteroid that comes closer to the sun than any other. Baade joined the staff of the Mount Wilson Observatory in 1931 and retired in 1958, 10 years after it had become the Mount Wilson and Palomar Observatories. On the night of June 26, 1949, he was working on a program with the newly completed 48-inch Schmidt telescope on Palomar Mountain that involved a 60-minute exposure of a region in the constellation of Scorpius near the bright star Antares. When he examined the plate the following day, he found a streak among the stars that had undoubtedly been made by an asteroid. Moreover, it was obvious from the length of the streak that the asteroid must be rather close to the earth [*see top illustration on page 107*].

Baade decided that the object was sufficiently remarkable to warrant trying for the two additional photographs needed for computing an orbit. The direction in which an asteroid is moving is often revealed by the nature of the photographic track: the track usually tapers from dark to light in the direction of travel. This is because the emulsion is more sensitive to sky brightness after it has been exposed to the image of the passing asteroid than before. With this clue and the knowledge that the object had passed the point in the sky directly opposite the sun, Baade could be quite certain that the object was moving in a retrograde, or westerly, direction. Accordingly two nights later, on June 28, Baade made another exposure slightly to the southwest of the object's previous position. His surmise proved correct—there was the streak again. It was an easy matter now to get a third observation on the night of June 30.

When Baade returned to the Mount Wilson and Palomar office in Pasadena, he asked Seth B. Nicholson and me if we would like to compute an orbit for the new body. Astronomers develop different specialties and computing orbits did not happen to be one of Baade's. Nicholson and I still retained a keen interest in the solar system; Nicholson in particular had become an expert at tracking down minor members of the solar system and determining their orbits. As a graduate student at the Lick Observatory in 1914 he had discovered the ninth satellite of Jupiter (J IX), and later at Mount Wilson he had found J X, J XI and J XII. I had become familiar with orbit work by helping him keep track of his satellites, which were always getting lost.

Our first step in computing the orbit of Baade's object was to measure its position with respect to the star images around it on the plate. We supposed that the positions of these stars would be readily available in one of the volumes of the star catalogue called the *Carte du Ciel.* Unfortunately for us, the particular volume we needed had apparently not been published as yet. (After all, the *Carte du Ciel* project had only been started in 1887.) This meant that we had to provide our own positions for the stars around the asteroid by measuring their distances in relation to stars in adjacent zones. As a result the positions we obtained for the asteroid were not as accurate as we could have wished. By July 5 we finally had three positions established for the asteroid that were reduced to the proper form for publication. We airmailed these to the Harvard College Observatory, which in turn relayed them on "announcement cards" to other observatories.

We were now ready to begin the computation of the orbit itself. This would merely be a preliminary orbit, suitable for predicting the whereabouts of the asteroid for about a month at the most. Unless we could secure additional observations to improve the orbit, Object Baade was likely to be lost forever. Nicholson had all the formulas written down step by step in an old notebook, a relic from his student days, with warnings about the traps and pitfalls besetting the unwary computer. One of the features of the formulas, which were based on a method devised by Pierre Simon de Laplace, is that the accuracy of the orbit can be checked by seeing how closely it will reproduce the original observations. If the observed and computed positions are not in satisfactory agreement, they must be made to agree by means of a differential correction. It is my experience that most orbits usually require such forcible treatment as a matter of routine. A preliminary orbit is imperfect not because of errors in computation but because the observations themselves are imperfect and the orbit method involves approximations.

From our preliminary orbit it was evident that the object discovered by Baade was a most exceptional asteroid; hence our increasing anxiety over its escaping us. Unless more observations were available very soon, it would be hopelessly lost. But now, to add to our difficulties, the moon had moved into the Scorpius region and would reach full phase on July 10. Its light would fog a plate so badly that another photograph was temporarily out of the question. We hoped that a few days later, when the moon would be out of the way, we might be able to pick up the object on a short exposure.

The first opportunity for a photograph would be Tuesday, July 12, although the moon would still be uncomfortably close. We completed work on the orbit and had predicted positions ready by late that afternoon. We immediately telephoned them to Bruce Rule, a colleague who was scheduled to use the 48-inch Schmidt that night and who had agreed to try for some plates of Baade's asteroid.

While awaiting news from Palomar we received a disquieting letter from Leland E. Cunningham of the University of California at Berkeley. He also had been doing some figuring with our three positions on the Harvard announcement card. His results showed that they could be represented about equally well by half a dozen orbits in which the semimajor axis ranged all the way from .9 astronomical unit to infinity! In other words, our orbit as it stood was virtually indeterminate and therefore of doubtful value for predictive purposes. This indeterminacy could only be removed by securing more observations. But how could we secure more observations if we didn't know where to observe?

On July 12 and 13 Rule succeeded in photographing the region in which the asteroid should be according to our calculations. Finding the asteroid on these new plates, however, was quite a different proposition from what it had been three weeks earlier. At that time

	BODE'S FORMULA	PREDICTED DISTANCE (ASTRONOMICAL UNITS)	ACTUAL DISTANCE (ASTRONOMICAL UNITS)
MERCURY	.4 + 0	.4	.39
VENUS	.4 + .3	.7	.72
EARTH	.4 + .6	1.0	1.0
MARS	.4 + 1.2	1.6	1.52
ASTEROIDS	.4 + 2.4	2.8	2.1-3.5
JUPITER	.4 + 4.8	5.2	5.2
SATURN	.4 + 9.6	10.0	9.5
URANUS	.4 + 19.2	19.6	19.2
NEPTUNE	.4 + 38.4	38.8	30.1
PLUTO	.4 + 76.8	77.2	39.5

BODE'S "LAW" is an empirical scheme that seemed to predict the distances from the sun at which planets should lie. It worked well for the six planets known to the ancients and its prediction was satisfied when Uranus was discovered by Sir William Herschel in 1781. The predicted position at 2.8 astronomical units was subsequently filled in 1801 with the discovery of the asteroid Ceres. The law collapsed with the discovery of Neptune and Pluto.

the asteroid was moving rapidly in a retrograde direction, so that it left an easily recognizable trail among the stars. Now the asteroid had almost reached its second stationary point, which meant that its motion with respect to the stars was scarcely perceptible [*see bottom illustration on page 107*]. Furthermore, it had moved into a section of the Milky Way that was particularly rich in stars. Each of the 14-by-14-inch Schmidt plates was covered with hundreds of thousands—perhaps millions—of star images. Our job was to find among those myriads the one particular image that happened to interest us.

The situation was not quite as hopeless as it sounds. We calculated the position of the asteroid on the plate and drew a box about an inch square around it. If our orbit was any good at all, the asteroid should be somewhere within that square inch. What we were looking for was an image elongated just enough to be distinguishable from the multitude of star images around it. We spotted half a dozen hopeful-looking images on the two plates, all of which on closer scrutiny turned out to be defects in the emulsion.

Finally we put the two plates on the "blink comparator," a device that makes the star images in the two fields merge when they are viewed through a single eyepiece. The two plates are then illuminated alternately so that the two fields are seen superposed in rapid succession. Since the stars are fixed in the sky their images remain stationary. If an object has moved between the two exposures, however, its image on one plate will not quite match its image on the other; hence the image will appear to "blink" or "jump." It would seem that such a procedure should have revealed the asteroid at once, but it was not that easy. Nicholson persisted, however, and finally found two displaced images that appeared to be real. Identification was confirmed beyond doubt when the positions of the images were found to be separated by the expected amount.

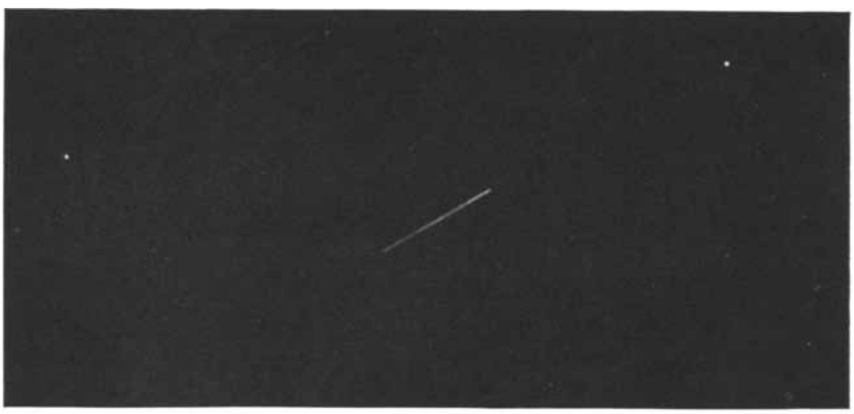
The new positions enabled us to derive an improved orbit in which we could place considerable faith, although it was somewhat disappointing in one respect. In our preliminary orbit the semimajor axis of the ellipse had come out to be less than one astronomical unit. The only other bodies in the solar system with a semimajor axis less than one astronomical unit are Venus and Mercury. Now in this asteroid we thought we had a third. When the orbit was corrected, however, the semimajor axis was just a little over one unit—1.066. The best value available today is 1.0777.

Even without this distinction Baade's object is remarkable enough. It is the only asteroid known to pass inside the orbit of Mercury; it approaches to within 17.4 million miles of the sun. At aphelion it travels beyond the orbit of Mars until it reaches a point 183 million miles from the sun. Its inclination to the plane of the earth's orbit is 23 degrees, about twice that of the average asteroid.

To define an orbit completely six numerical quantities are necessary [*see illustration on page 110*]. These can be expressed in a variety of ways, depending on how they are to be used in the process of computation. Five of the elements specify the size, eccentricity and orientation of the ellipse in relation to a standard reference system. In the case of asteroids this reference system is the plane of the earth's orbit. The sixth element tells where on the ellipse the asteroid or other body can be found at a particular time, usually the time of passing the perihelion.

The name of Icarus for the new asteroid was suggested independently by R. C. Cameron of the University of Indiana and G. E. Folkman of Mount Clemens, Mich. The privilege of selecting a name rested, of course, with its discoverer. Baade liked the name Icarus, and so it was adopted.

The date of the next close approach of Icarus to the earth can easily be found from the respective orbital periods. The period required for Icarus to travel once around the sun is 406 days, or 1.119 years. A little arithmetic shows that 19 revolutions of the earth



ASTEROID EROS, discovered in 1898 by the German astronomer Gustav Witt, was the first asteroid known to pass inside the earth's orbit. This photograph was made in 1931 by George Van Biesbroeck, using the 40-inch Yerkes refracting telescope, when Eros came to within 16.2 million miles of the earth. The asteroid is approximately 15 miles long and five miles wide.

are equal approximately to 17 revolutions of Icarus ($17 \times 1.119 = 19.023$). This means that if Icarus and the earth are close together on a certain date, they will be close together again 19 years later. Since the last close approach was in 1949, the next one will occur in 1968, on June 15, when the minimum distance between the two bodies will be four million miles [*see illustrations on page 111*]. In its present orbit Icarus could come to within 3.5 million miles of the earth on another occasion.

I have left to the end any mention of the origin of asteroids, because this is still a matter of speculation. In 1802 the German astronomer H. W. M. Olbers, the discoverer of Pallas and Vesta, advanced the hypothesis that the asteroids are fragments of a former planet revolving between Mars and Jupiter that had been shattered. Perhaps the most remarkable feature of Olbers' hypothesis is its extraordinary vitality in view of the total lack of evidence to support it. If the asteroids had such a catastrophic origin, their orbits, if undisturbed, would all intersect at the point of disintegration. All attempts to locate this point, however, have proved futile for the simple reason that all trace of it would have been erased long since by the perturbing effect of Jupiter and Saturn. If the asteroids had once formed a primeval planet, its mass could hardly have exceeded that of the moon. A hypothesis that has been received with more favor is that the asteroids originated not from the disruption of a single planet but from a collision between two planets, or possibly a series of collisions among several planets.

The asteroids have demonstrated their value to astronomy in a variety of ways. They have stimulated cooperation among astronomers. They have presented astronomers with problems of great interest in celestial mechanics. The discovery of Eros enabled us to get the first accurate value for the length of the astronomical unit, as well as to improve our values of the ratio of the mass of the earth to the sun and of the moon to the earth. Eventually Icarus should furnish us with an excellent test of the general theory of relativity. In addition the asteroids may provide clues to the origin of the solar system. In time, no doubt, we shall wish to send out a space vehicle to photograph an asteroid at close range and see what one really looks like. A photograph of Ceres on the first night of the 21st century would make a fitting commemoration of Father Piazzi's discovery.

Let's explore two questions you might have about SYSTEM/360 as a scientific computer.

QUESTION #1:

Isn't SYSTEM/360 basically a commercial machine that must be adapted to work on scientific or mathematical data processing problems...and doesn't it come with a lot of features scientific workers don't need?

QUESTION #2:

Don't scientists and engineers have special needs that the all-purpose SYSTEM/360 does not meet?

THE FACTS:

SYSTEM/360 is a binary machine—a *word* machine—well suited to scientific computing.

Many of its special features are tailored to your needs.

SYSTEM/360 is an all-purpose machine because it adapts to many special purposes. Everything about it, machines, programming, system organization, is modular.

You are free to select or reject its many optional features.

SYSTEM/360 has the speed you need. It gives you a choice of speeds.

It works like a word machine for fast computing . . . or a character machine for fast compiling.

It handles big problems without segmentation because it has the giant memories you need—modular memories. You choose the right size for your application.

SYSTEM/360 has the interrupt, program relocation and automatic checking and protection features you need to process information reliably in real time...to time-share processors, memory or files.

Two new models are specially designed for time-sharing applications.

This system lets you use either of two precisions in fixed point and floating point arithmetic . . . and variable field length in decimal arithmetic.

It lets you quickly and easily expand your system . . . or reduce its size and complexity when your needs change.

All these abilities interact to make SYSTEM/360 the most powerful and versatile scientific problem-solving tool we ever created.

That makes it difficult to describe the system a feature at a time.

But we'll try. Right now.

Speed isn't everything—but we have it

Solid Logic Technology—our name for the advanced microcircuits used in SYSTEM/360—is the most practical combination of speed and performance available today.

But we designed SYSTEM/360 so that new technologies can be incorporated without changing the way you use the system.

In fact, IBM engineers have already developed advanced circuits with switching speeds as fast as one and one-half nanoseconds.

Our fastest processor accesses a full 64-bit double word in half a microsecond. Interleaved memory on this processor gives you even faster effective access time.

SYSTEM/360 has the raw speed you need, whether you're inverting a large matrix, designing by iterative methods or applying heuristic techniques.

But raw memory speed doesn't buy you much all by itself.

Today, registers operate faster than memory. So we designed SYSTEM/360 with a full set of register-to-register instructions to reduce the number of times the system must move data out of memory. Even in a relatively simple polynomial evaluation, such as:

$$\mathbf{Y = A+X\,(B+X(C+X(D+X(E))))}$$

an ordinary computer would be moving the value, X, out of memory repeatedly. In SYSTEM/360, you'd move X out of memory only once and solve the problem faster.

SYSTEM/360 contains sixteen 32-bit general registers. You use these registers for binary arithmetic as well as for indexing and address arithmetic. (In SYSTEM/360, you can address over sixteen-million 8-bit bytes using only 16 addressing bits per instruction.)

The system also includes four 64-bit floating-point registers. These registers can handle either 32-bit or 64-bit floating point operands.

Data channels also help speed problem-solving. They are, in effect, small computers that relieve the main processor of time-consuming I/O operations and allow computing and I/O operations to go on at the same time.

The selector channels handle up to 256 high-speed input/output devices, like tape drives. Each channel can handle one device at a time. Data rates range from 250,000 to 1.2 million 8-bit bytes per second.

The multiplexor channel permits up to 256 low-speed devices—such as data communications terminals for remote computing—to time-share the data path to the central processor. All 256 can be operating simultaneously.

One of a series briefly describing GM's research in depth

How does a driver handle an automobile?

What combination of directional control characteristics is best used by the driver?

At least 27 interacting design parameters . . . inertias, masses, mass distributions, wheelbase, tire design, steering ratio, roll centers . . . affect the directional control of a car.

Fortunately, our researchers have developed equations to approximate these in a simplified mathematical model and have successfully described responses of many distinctly different vehicle configurations by this technique.

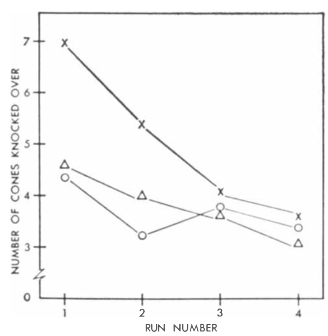
Using this information, GM Research engineers and psychologists are studying driver responses with the aid of a car having variable stability and control. Directional control characteristics can be varied quickly. Easily. Through a maze of potentiometers, vehicle motion sensors, and servos in the steering system, this car can assume the driving characteristics of just about any standard vehicle, or act like no car ever built. It can seem like a compact car . . . or a heavily loaded station wagon.

In a pilot study, the variable car was adjusted to represent each of three vehicles to drivers who took it through a narrow winding course. One interesting result: For significantly different vehicle handling characteristics, driver performance was nearly the same after only a short learning period—excellent evidence of the human operator's great adaptability.

Learning to understand such complex interactions of man and his machines is one continuing objective of General Motors research in depth.

General Motors Research Laboratories

Warren, Michigan



Road data for three simulated vehicles. Averages for drivers traveling 30 mph through course marked by traffic cones.

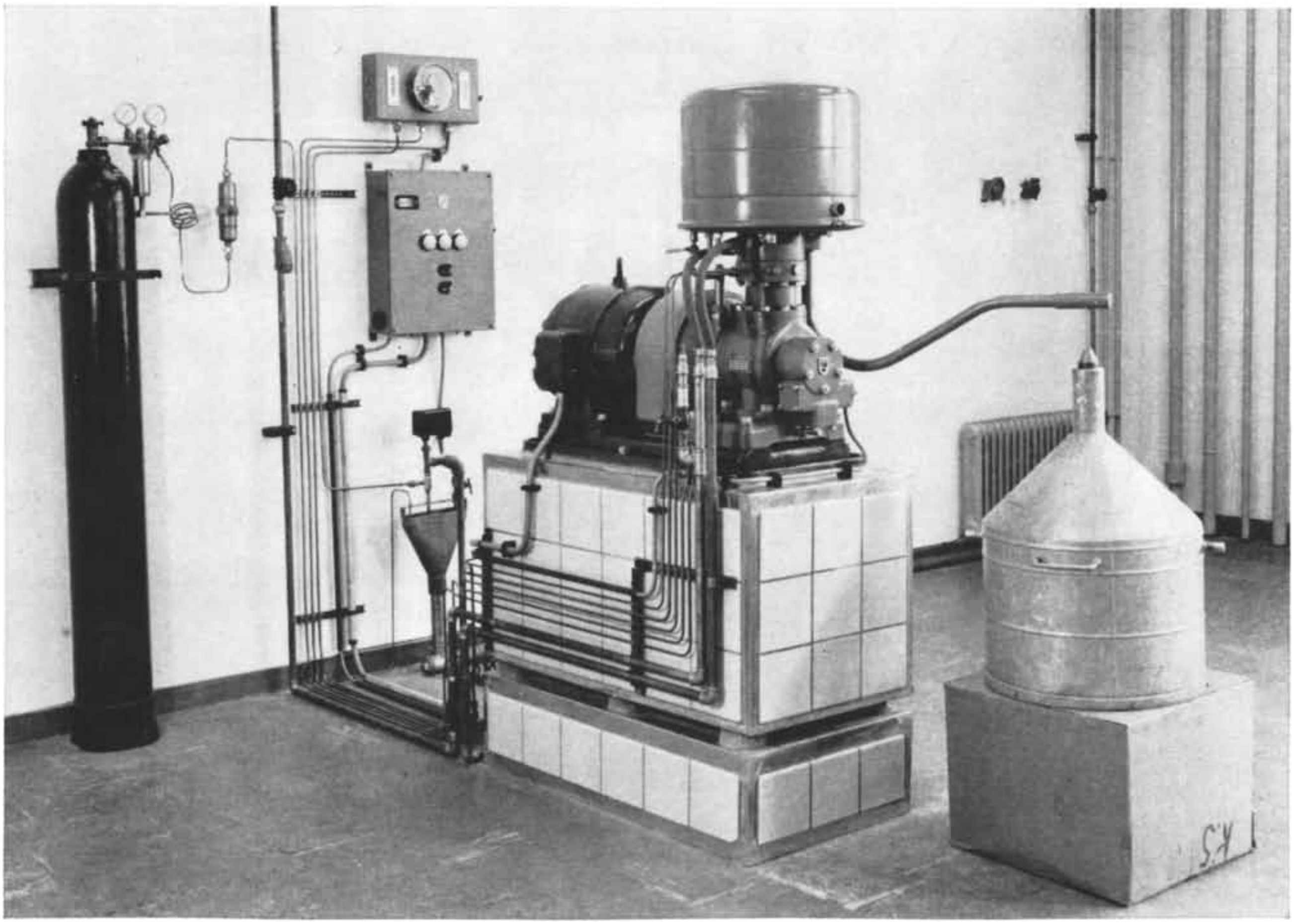
The Stirling Refrigeration Cycle

In 1816 Robert Stirling invented an engine that operated by heating and cooling air in a closed cycle. The cycle has now been "reversed" in an efficient machine for cooling things to very low temperatures

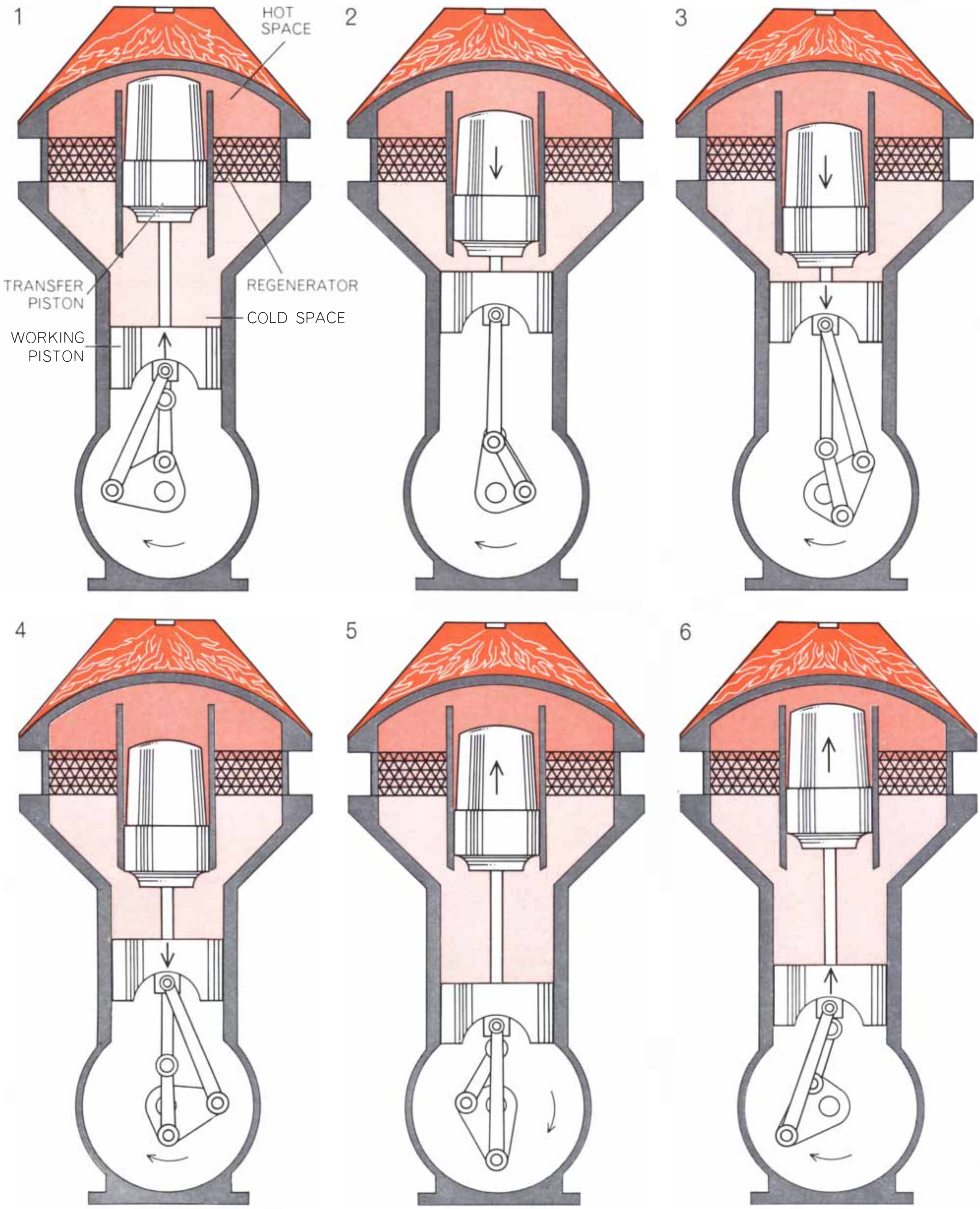
by J. W. L. Köhler

The most spectacular technological advances of the past 20 years rest largely on principles that were discovered only a little earlier. Among many cases in point are the technologies of nuclear power and solid-state electronics. There are exceptions; the laser, for example, springs from the discovery of stimulated emission by Albert Einstein in 1917 and superconducting magnets arise from the discovery of superconductivity by Gilles Holst and Heike Kamerlingh Onnes in 1911. Even these discoveries are new compared with the invention underlying the theme of this article. That invention was the hot-air engine, a simple but elegant machine patented in 1816 by Robert Stirling, who was a minister of the Church of Scotland.

Stirling thought of the hot-air engine as a device for converting heat into mechanical power, like its contemporary the steam engine. After nearly a century and a half it turns out that the hot-air engine's basic principle—the Stirling cycle—is also a means of refrigeration



FIRST PHILIPS REFRIGERATOR using the Stirling cycle was an air liquefier built in 1954. Cylinder at left provided helium used in the cycle. Dome at top contained a purifier for air drawn in from the room for liquefaction at a rate of 7.5 liters per hour.



HOT-AIR ENGINE that was a forerunner of the Stirling refrigeration cycle is depicted schematically according to the principles of an engine patented by Robert Stirling in 1816. The engine moved air between a cold space and a hot space in four overlapping phases. In the first phase (*1 and 2*) air was compressed in the cold space by a working piston and moved, with the help of a transfer piston, into the hot space, where in the second phase the air was heated by an outside burner. As a result the gas expanded against the working piston (*3 and 4*); it was this third phase that provided the driving force of the engine. Finally (*5 and 6*) the transfer piston moved the air back into the cold space. The regenerator, or heat exchanger, substantially reduced fuel consumption by storing unspent heat as the air passed into the cold space and returning the heat as the air moved again into the hot space.

with exceptional advantages at very low temperatures. One of the reasons why this discovery was so long in coming is that the materials and mechanical concepts needed to make the hot-air engine a rival of the steam engine and the later internal-combustion engine were slow to evolve. Perhaps a more important reason is that the need for the low temperatures at which the Stirling cycle is most efficient has arisen only recently in technology and the laboratory. Today low temperatures are routinely required for such purposes as cryogenic experiments, the large-scale liquefaction of gases for rockets and the long-distance transportation of foods. Even with this stimulus, however, the recognition of the Stirling cycle's usefulness in refrigeration came only after the application of modern research techniques.

Stirling's engine of 1816 operated on classic principles concerning the heating and cooling of a gas, in this case air. A heated gas expands; if it is expanded against a piston or in a turbine, it will do work. The gas also cools as it expands, so that the basis for a cycle of operations exists if an arrangement is made to move the gas back and forth between a cool space and a hot space. Stirling's arrangement was a closed cylinder in which the air went through a cycle of four overlapping phases [*see illustration on opposite page*]. First it was compressed at the cool end of the cylinder by a working piston. Then it was moved by the working piston and a transfer piston to the other end of the cylinder, where it was raised to a high temperature by heat from an outside burner. In the third phase the heated air expanded against the working piston, thereby providing the driving force of the engine. Finally the air was returned to the cool end of the cylinder with the aid of the transfer piston, and there the cycle began anew.

The processes of heating and cooling were appreciably augmented by what Stirling called an "economizer." This device, which he was the first to include in an engine, functioned on a principle that is now known as "regeneration" and is used in various kinds of prime movers and in gas-separation plants. The economizer, or regenerator, was a heat exchanger; in Stirling's engine it consisted of a series of thin, closely spaced iron plates. Its function was to absorb unspent heat from the expanding air as the air left the hot end of the cylinder and to give the heat back as the air returned from the cool end of the cylinder. This device substantially reduced the fuel consumption of the engine.

As long ago as 1834 it was recognized that if one took away the burner but kept the engine running by some other means, the Stirling cycle would function as a refrigerator. The gas in the cylinder would continue to go through the same cycle as before, absorbing heat in the expansion phase, except that now the source of heat would not be a burner but would be whatever one wanted to cool. Sometimes this process is described as "reversing" the hot-air engine. The term is rather misleading because the Stirling cycle is not reversed. What is reversed is the purpose of the user: instead of putting heat into the cycle for the purpose of taking mechanical energy out, he is putting mechanical energy in for the purpose of absorbing heat.

The major functional difference between a hot-air engine and a refrigerating machine when both employ the Stirling cycle lies in the temperature at which the expansion phase takes place. In the hot-air engine the expansion phase occurs at a temperature above that of the environment. In the refrigerating machine the expansion phase occurs below the environmental temperature.

Against this background the reader should be able to follow the refrigeration cycle as it is depicted in the illustration on the next page. The illustration shows four positions in the cycle of a two-piston machine. Apart from the pistons, each panel shows from right to left five interconnecting elements: a compression space, a cooler, a regenerator, a freezer and an expansion space. The cycle begins with the input of mechanical energy from a motor to the compression piston, which compresses the gas at room temperature. Next the gas is transferred to the cold space, passing through the cooler, which discharges the heat of compression to the outside, and through the regenerator, which cools the gas to the working temperature (the temperature of the expansion space) by temporarily storing its heat. In the third phase the gas is expanded in the expansion space, thereby becoming still colder by a few degrees.

The standard terminology of refrigeration describes this process as the "production of cold." As a result of the cold thus produced the gas is enabled in the fourth phase to absorb heat from whatever the machine is designed to cool. During the fourth phase the gas is returning to the compression space. On the way it passes through the freezer, where the absorption of heat from the outside takes place. Next the gas flows through the regenerator, where it picks up the stored heat, emerging from the regenerator at room temperature and returning to the compression space for the start of a new cycle.

In such a cycle it is necessary to have the pistons operating somewhat out of phase with each other, because if the machine is to act as a refrigerator, the expansion space has to lead in phase with respect to the compression space. This phase displacement can be achieved by designing the crankshaft so that the throw for one piston is approximately at right angles to the throw for the other. Since each piston is driven by a crankshaft, its motion is harmonic: its speed varies smoothly from a stationary condition as it begins a stroke to a maximum in the middle of the stroke and back to a stationary condition at the end. As a result of this harmonic movement the four phases of the cycle tend to merge somewhat, but this has practically no influence on the effectiveness of the process.

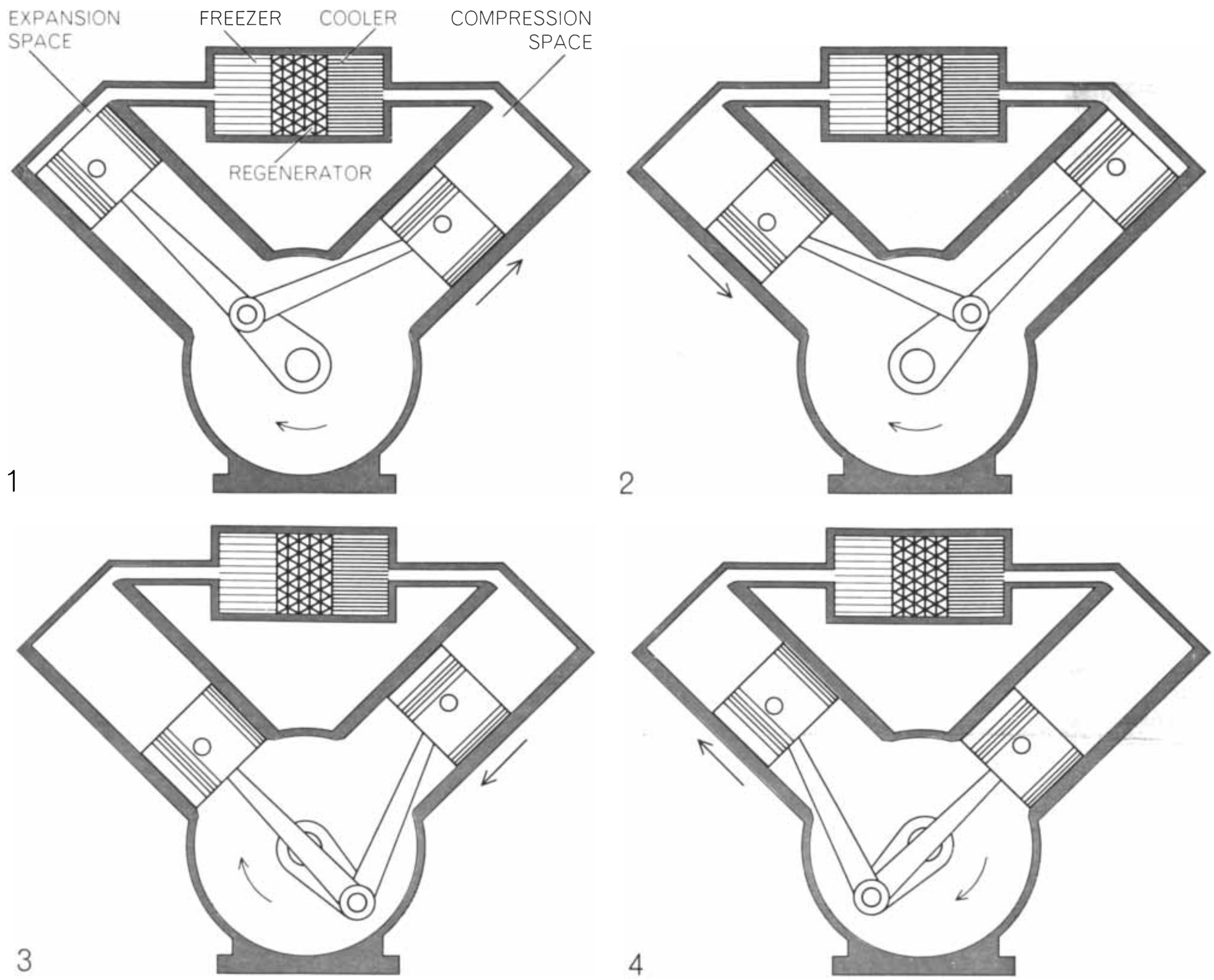
In view of the fascinating simplicity of the Stirling cycle it is no wonder that many people tried to put it to work for refrigeration. Some refrigerators were in fact constructed on this principle; a report in 1873 described one that had been running for 10 years in a brewery. From the fact that the Stirling concept made little impact on refrigerating technology, however, it is evident that the efficiency of these early machines was unsatisfactory. Certainly they were not operated to achieve the very low temperatures for which the Stirling cycle has proved to be particularly suited.

Such was the situation in 1938, when H. Rinia and his colleagues at the Philips Research Laboratories in the Netherlands began reconsidering the Stirling cycle as a hot-air engine. Their objective was to provide a simple small generator to power a radio set. This work, carried on secretly during the war, resulted in among other things a one-horsepower single-cylinder engine with promising qualities.

In the course of this research it was observed that all the engines cooled vigorously when they were driven by an electric motor. In 1945 Rinia and F. K. du Pré converted the one-horsepower unit into a refrigerator and obtained temperatures in the liquid-air range: −190 degrees centigrade, or 83 degrees Kelvin (degrees centigrade above absolute zero). Thereupon research on the Stirling refrigerator was assigned to a separate group and I was invited to take charge of it. I kept in mind an observation Rinia made in introducing me to the group; it was to the effect that our hot-air engines cooled marvelously, whereas when we built machines expressly designed as refrigerators, they were unsatisfactory. I designed my first models along the lines of the hot-air engines, and as a result they never failed as refrigerators.

In the ensuing years the engine and the refrigerator groups sought to obtain more fundamental knowledge, both theoretical and practical, about the Stirling cycle. The large number of people involved prevents me from mentioning all their names. At length in 1950, after struggling for two years with a puzzling regenerator effect, C. O. Jonkers and I obtained the first drops of liquid air from a Stirling-cycle refrigerator. Four years later a small air liquefier for laboratory use was beyond the engineering stage [*see illustration on page 119*]. Before turning to the applications the Stirling cycle has found in refrigeration and those that appear possible, I should like to describe some of our experiences in gaining a better understanding of the cycle.

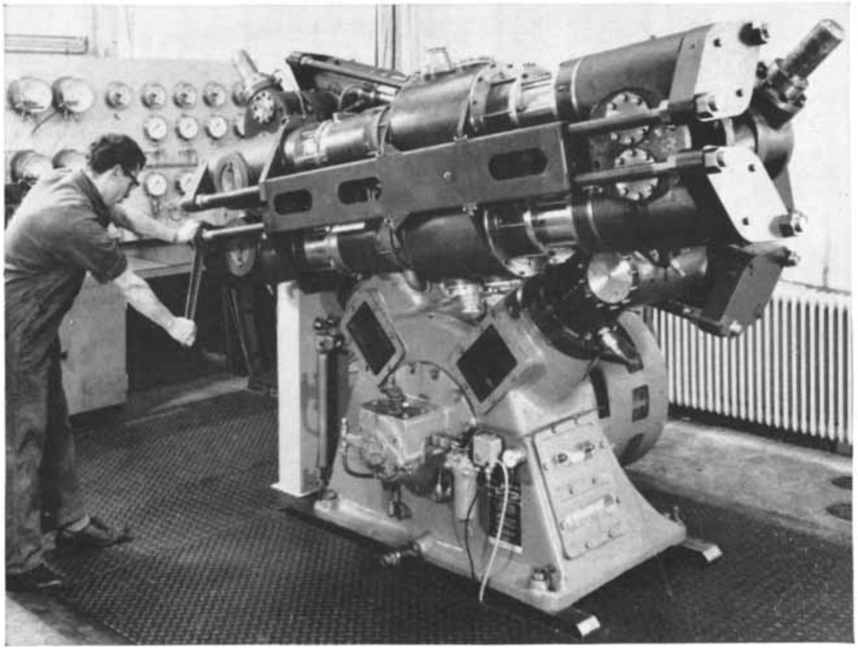
One of our first efforts was to recapitulate the properties that made the cycle seem so attractive. Among several such properties, we found five to be particularly intriguing. One was the possibility of managing the complicated process of refrigeration in a single space, simply through the out-of-phase movement of two pistons. A corollary was that the system would require no valves; as a result design, maintenance and handling—all important considerations—would be very simple. Third, the machines would be extremely compact because they would operate at high speed and high pressure (output being roughly proportional to speed and pressure).



STIRLING REFRIGERATION CYCLE is depicted schematically as it would progress in a machine involving out-of-phase operation of two pistons. The cycle begins (*1*) with compression of a gas at environmental temperature; the motive force for the compression is provided by an outside source, such as an electric motor. Thus increased in pressure the gas moves (*2*) through a cooler, which dissipates the heat of compression; a regenerator, which cools the gas nearly to the refrigerating temperature, and a freezer. Then the gas is expanded in the expansion space (*2 and 3*), becoming still cooler as a result of the mechanical work it does against the expansion piston. At the end of expansion the piston moves the gas back to the compression space (*4*). On the way through the freezer the cold gas absorbs heat from whatever the machine is intended to cool; this process in the freezer is sometimes called the "discharge of cold." Passing through the regenerator, the gas picks up the stored heat and is returned to environmental temperature.

This latter property would provide the added advantage that the output could be controlled easily by regulation of the pressure, a feature that is absent in most other systems. High speed and high pressure could be promoted by using light, well-behaved gases such as hydrogen or helium as a working fluid inside the machine.

We recognized, however, that even in combination these properties would not warrant the use of the cycle for refrigeration unless the efficiency of the process were reasonable. To our great satisfaction we found that the efficiency was indeed reasonable, even outstanding. In the illustration on the next page the efficiency of several refrigerative processes is shown for various temperatures. One can see that below 170 degrees Kelvin the Stirling cycle has a higher efficiency than any other process. At 77 degrees K., the temperature at which nitrogen liquefies, the efficiency is 30 percent; the optimum value is 42 percent at about 130 degrees K. The fact that our predecessors used the Stirling cycle in a far higher temperature range partly explains why they had no lasting success.



INDUSTRIAL REFRIGERATOR using Stirling cycle has four separate thermodynamic systems, which are the sloping cylinders at top, and a "V" drive, partly visible below them.

Having satisfied ourselves that the Stirling cycle deserved further investigation, we undertook a thorough analysis of the cycle. We were particularly concerned with establishing its losses, by which I mean the sources of its inefficiencies. Obviously any steps that reduced inefficiency would increase the attractiveness of the cycle for refrigeration. Although all the members of our group contributed to this effort, the main burden was carried by W. F. Schalkwijk and L. de Lange.

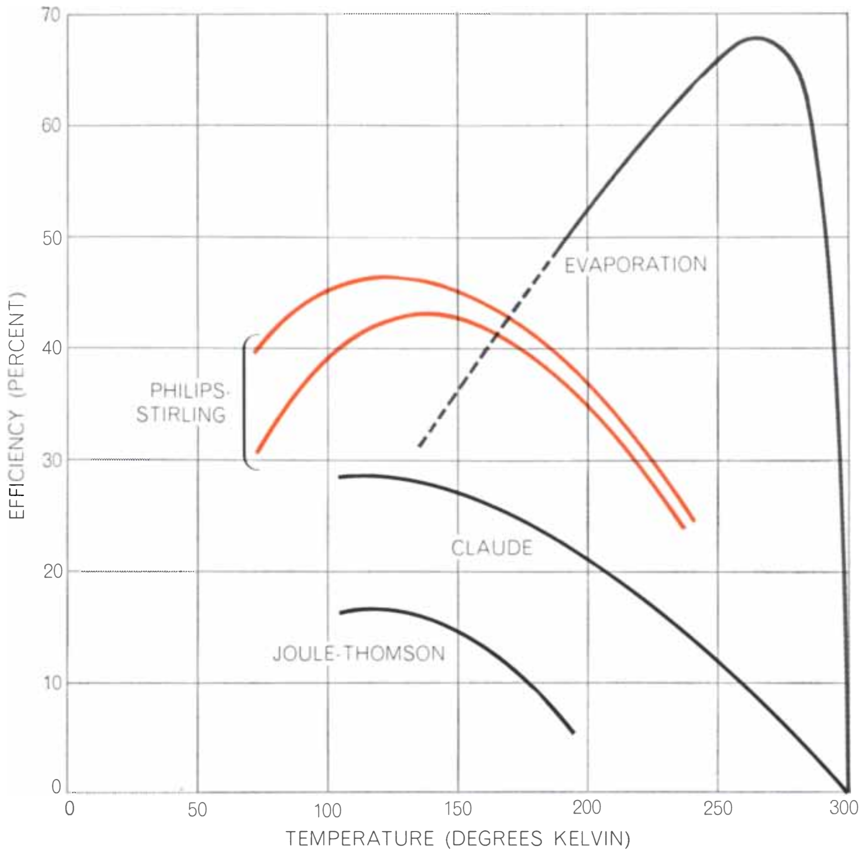
The losses can all be placed in one or another of four categories: the mechanical loss that occurs as a result of friction in any machine with moving parts; a similar energy loss occurring in this instance because of friction between the flowing gas and the obstacles it must pass; losses arising from nonideal heat transport; insulation losses. The first two categories need no further explanation, but the others do. The problem of nonideal heat transport arises in the following ways: the cold produced in the cycle must be transported out of the machine in order to achieve refrigeration of an object or a substance, and the heat of compression must also be dissipated outside the machine. Both types of transport are carried out by heat exchangers, which function by the notoriously nonideal processes of heat transfer and heat conduction. As a result of this deficiency the machine operates with a temperature that is higher than needed in the compression space and lower than needed in the expansion space. This is significant because the efficiency of the machine tends to drop as the ratio between the temperatures of the two spaces increases.

Insulation loss refers to everything that involves a leaking of cold. Some of it is simply what the name implies; efforts at insulation cannot be wholly successful. This category of loss, however, also includes the loss that occurs in regeneration. I shall describe the regeneration loss at greater length because of its dramatic influence on the performance of the machine.

In the regenerator, which now consists of a mass of copper wires each .008 inch in diameter, a quantity of heat must be absorbed and rejected in each cycle. Because heat transfer is not ideal this process is less than 100 percent efficient. The heat not absorbed by the regenerator is carried along with the gas into the cold space, so that the gas arrives in the cold space too hot. Here, then, is the regeneration loss, which of course reduces the ideal cold production. If one works out the impact of the loss mathematically, using a compression temperature of 300 degrees K. and an expansion temperature of 75 degrees K., it turns out that a 1 percent inefficiency in the regenerator induces a loss of 21 percent of the ideal cold production. The figure increases to 98 percent if one assumes an expansion temperature of 20 degrees K., the temperature at which hydrogen liquefies. In other words, at 20 degrees K. the regenerator would consume virtually the entire production of cold. When one recognizes that the regenerator is nonetheless almost 99 percent efficient and that it cools the gas at a rate of 20,000 degrees C. per second, one realizes that the regenerator is in fact the heart of the machine. Research on regenerators ranks high in our group; it has been done successively by B. D. Schultz, J. Mulder and G. Vonk.

Because the regenerator has such a pronounced effect on the efficiency of a Stirling-cycle refrigerator, the designer of the machine must seek to ensure that the gas transport occurs as much as possible through the regenerator. If only 1 percent of the gas leaked past the expansion piston instead of going into the regenerator, the effect would be equal to that of the loss that normally occurs in a regenerator, that is, 21 percent of the ideal production at 75 degrees K. Losses of this kind must be avoided at all costs. Because the usual kind of piston always leaks to some extent, it is inadvisable to use such a piston in the expansion phase.

Here another invention by Stirling comes to the rescue. It is his "displacer," which is the transfer piston mentioned at the beginning of this



REFRIGERATION EFFICIENCIES of various processes are compared. It is evident that the Philips-Stirling process has superior efficiencies at extremely low temperatures. The lower of the two curves for the Philips-Stirling process represents the performance of a small machine built for laboratory use; the upper curve, that of a large industrial machine.

article in connection with the hot-air engine of 1816. The function of a displacer is shown in the illustration on the opposite page; there one sees the working space of the cylinder closed by a single piston and subdivided into the compression space and the expansion space by the displacer. During the cycle the displacer moves the gas from one space to the other and back again. The advantage of a displacer lies in this: a normal piston, fitting tightly in its cylinder, has a much higher pressure at its working end than at its other end, a condition that promotes leaking of gas along the sides of the piston; in contrast the only pressure difference that occurs across a displacer piston is the small amount caused by the obstructions the flowing gas encounters in the heat exchangers. Hence the leakage past the displacer is small and can be accepted.

The illustration shows another of Stirling's useful inventions. This is the isolation of the cold space by means of an insulating hood on the displacer. The hood fits in the cylinder with a small gap and prevents cold gas from reaching warmer parts of the machine.

Our first machines performed satisfactorily down to about 77 degrees K., and occasionally we achieved cooling to as low a level as 45 degrees K. It seemed impossible, however, to go lower. This situation disturbed us because theoretical studies of the Stirling cycle's capabilities indicated that appreciably lower temperatures should be within reach. About five years ago we embarked on an effort to build machines that would come closer to the theoretical possibilities. We eventually produced a miniature cooler that reached 25 to 30 degrees K., but it could only be regarded as a forerunner of still better machines.

It was plain that more radical measures were needed to obtain 20 degrees K. and lower with good efficiency. My colleague G. Prast therefore approached the problem from a different direction. He used an extension of the Stirling cycle devised in the late 1940's by H. Fokker and me and preliminarily investigated earlier by H. Verbeek [*see illustration on opposite page*]. The cycle involves a displacer system as before, but now the top of the displacer has an extension with a smaller diameter. Thus two end faces are created, one ring-shaped and one flat; similarly, there are two expansion spaces, one ring-shaped and one normal.

The result is a two-stage expansion process. Part of the compressed gas is expanded in the ring-shaped space; the rest continues its way through a second regenerator and freezer to be expanded at the top. The first expansion covers the loss of the first regenerator and thereby provides a fresh start for the rest of the gas. Moreover, the temperature difference bridged in the second stage is small, and so therefore is its loss. As a result the final stage has a nice surplus of usable cold.

It was a great day when our prototype machine built on these principles made its first run and nearly came up to expectations. At 20 degrees K. it produced 100 watts of cold—only 15 percent off the mark at which we had aimed. The efficiency of the machine at that level was 17 percent. Interestingly the machine proved able to cool down to 12 degrees K., its lowest temperature, within 20 minutes of starting.

Extending the Stirling cycle with a two-stage expansion process opens the way to an important improvement in the cycle's refrigerative qualities. With a slight modification of design the machine will produce useful cold at the intermediate stage without unduly reducing the output of the final stage. This property can be used to advantage for cooling down a continuous stream of gas, as for example in liquefying hydrogen and helium.

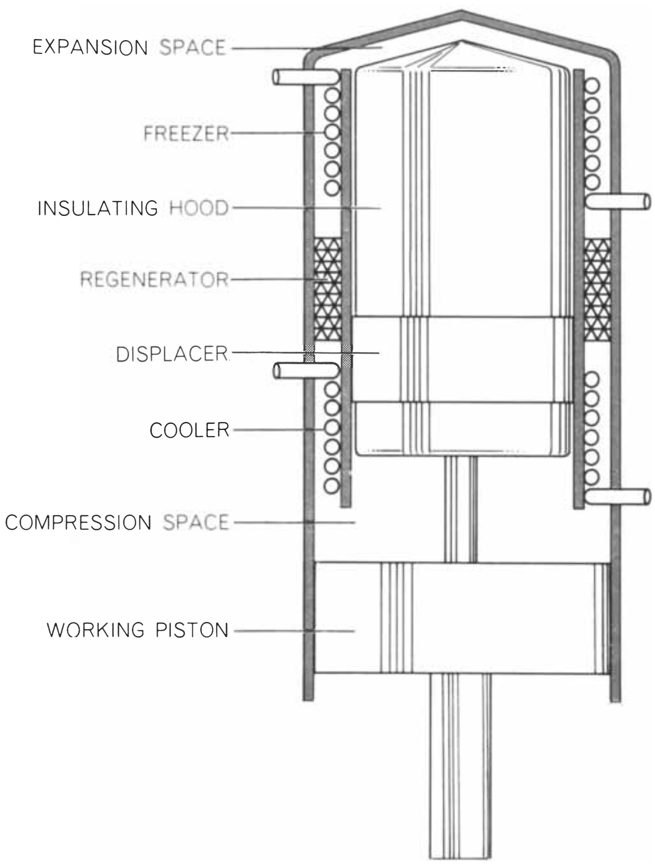
What I have said so far suggests the capabilities of the Stirling refrigeration cycle, which textbooks on thermodynamics were dismissing 25 years ago as "obsolete" and "of academic interest only." I would be remiss, however, if in my enthusiasm for unveiling Cinderella I avoided mentioning her blemishes. The Stirling cycle has three principal shortcomings. First, its extreme compactness, although in many respects a virtue, makes discharging the cold quite a problem. In fact, discharging its cold is simple only when the machine is used to liquefy a gas; the efficiency figures I have given are for this use. When the machine is used merely to cool a gas or a liquid, heat transfer falls short and losses arise.

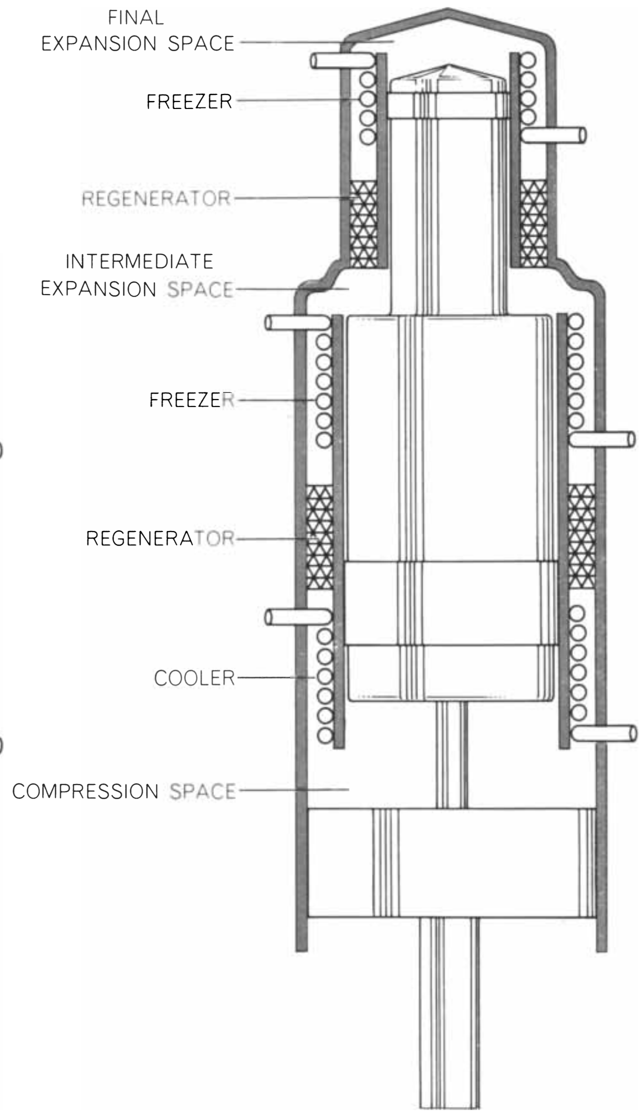
Second, the high efficiency of the machine can only be realized by careful manufacture and assembly. This, together with the intricacy of the heat exchangers, tends to make the machine expensive. Here one sees yet another confirmation of the general rule that the gap between the thermodynamic efficiencies theoretically attainable and those economically attainable is substantial. Finally, the operations of the cycle are difficult to analyze mathematically and therefore difficult to evaluate in performance. The cycle behaves as a unit with both cooperating and conflicting effects, whereas other systems consist of noninterfering units connected in series and are therefore easy to analyze. The difficulty of analyzing the Stirling cycle is certainly one of the reasons for the belated recognition of the cycle's attractiveness.

In spite of all improvements the Stirling-cycle refrigerators I have described so far were suitable mainly for use in laboratories rather than in industry, where the demand is for machines capable of heavy duty and long endurance. Recently, however, the Stirling cycle has made the leap into industry. The success of this venture is attributable to A. A. Dros and his colleagues in the Philips engineering department for refrigeration.

Dros proposed a revolutionary step in design. It was to transfer hydraulically the movement of the master pistons of a standard compressor drive to the pistons of the Stirling machine. His reasoning was that the best guarantee for obtaining high reliability is to start with a well-established drive and that a hydraulic linkage is unlikely to present problems of endurance. The scheme was seriously jeopardized, however, by the lack of a suitable piston seal to prevent the penetration of oil into the working space of the Stirling cycle.

Here the timely invention of such a seal by H. H. M. van der Aa, H. J. C. van Beukering and J. A. Rietdijk of our laboratory played a key role. In principle it is as simple as it is elegant. It employs the well-known device of a rolling diaphragm [*see illustration on page 127*] but overcomes the difficulty presented by the fact that such a diaphragm can withstand only small pressure differences. The invention involves supporting the diaphragm with an incompressible fluid, such as oil, in a volume that remains constant during the movement of the piston. The constant





PISTON ARRANGEMENTS evolved for the Stirling refrigeration cycle include a displacer piston (*left*) and a modified displacer system (*right*). The function of a displacer piston is to help move gas back and forth between the compression space and the expansion space without the leakage of gas that occurs past a tight-fitting piston, such as the working piston, because of the large pressure difference between its working face and its other face. The insulating hood helps to keep cold gases from coming into contact with warm parts of the machine. In the modified displacer system the displacer piston has an extension of small diameter. As a result there are two expansion spaces and cooling takes place in a two-stage process that produces significantly lower temperatures.

THE LASE

The amazing laser makes light beams which weld, measure, balance, heat, survey, detect, communicate, time, sterilize, map, machine, heal, analyse, search, melt. The world's first working laser was built by Hughes.

Even science fiction writers were unprepared for the laser when it burst on the scientific world in 1960. Few would have predicted that man could indeed create light that was coherent—whose waves all "marched in lockstep." Light so coherent that a beam sent from a laser is only a few feet wide ten miles away. Whose energy could be controlled to generate instant heat millions of times hotter than the sun.

Today the laser has caught the imagination of researchers in hundreds of fields. Dentists are "welding" fillings into teeth. Watchmakers are drilling tiny holes in ruby jewels in microseconds instead of hours. The human voice as well as pictures have been transmitted on a laser beam. Experts calculate one beam could carry all the telephone conversations being made at this moment.

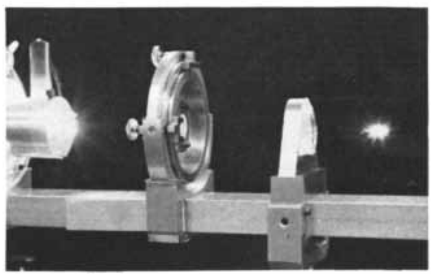
One of the first practical uses of the laser is the Hughes Colidar (Coherent Light Detection and Ranging). The first laser rangefinder, it can measure distances with accuracy and speed never before obtainable. Several versions, for use by troops, in tanks and helicopters, pinpoint targets several miles distant.

In the new field of microminiaturization, Hughes laser welders offer clear advantages. Joining the tiny bits of metal for interconnections between thin film elements, for example, is virtually impossible with other methods. But the laser can fuse wires just 0.0005" in diameter, join dissimilar metals, and even go through the glass envelope of a display tube to weld otherwise inaccessible connections.

The world's first working laser, built by Hughes, used a ruby which "lased" in one color—red. Latest example of Hughes research is the achievement of the first "variable" laser which produces 60 new colors. Using a "noble" gas—such as argon, xenon, krypton and neon,

LASER RANGER IN GUN CONFIGURATION FIRES A LIGHT BEAM TO GIVE PRECISE RANGE OF OBJECTS UP TO TEN MILES AWAY — RANGE IS INSTANTLY READOUT BY OPERATOR.

NEWEST HUGHES LASER DEVELOPMENT HAS JUST ADDED 60 COLORS TO THE GAS LASER'S CAPABILITY — FILLING THE PREVIOUS GAP IN LIGHT SPECTRUM. THIS OPENS GREAT NUMBERS OF NEW LASER APPLICATIONS.



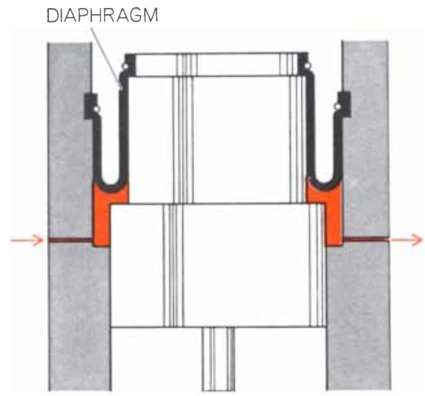
AIR SPARK, PRODUCED BY 100,000,000 WATTS FROM HUGHES LASER, WHEN AIR MOLECULES ARE IONIZED FOR SPLIT SECOND

THIN FILM CIRCUIT (RIGHT) OF ALUMINUM IS JOINED BY MICROSCOPIC WELDS IN NICKEL RIBBON. THE ABILITY TO WELD DISSIMILAR METALS IS JUST ONE OF THE LASER'S ADVANTAGES IN METALWORKING. (CIRCUIT SHOWN IS TWICE ACTUAL SIZE.)

Creating a new world with electronics

HUGHES

HUGHES AIRCRAFT COMPANY



ROLLING DIAPHRAGM provides a seal between the hydraulic drive of an industrial refrigerator and the gas used in the Stirling cycle. A key invention involved supporting the flimsy diaphragm against the heavy pressures of the gas by means of an incompressible fluid such as oil (*color*), which as the diaphragm moves is kept virtually constant in volume by steps built into the cylinder wall. Some oil is moved in and out of the cylinder to maintain a small pressure difference that keeps the diaphragm from creasing. The arrows indicate the points at which the oil enters and leaves.

volume is achieved by steps built into the piston and the cylinder wall. A small pressure difference is maintained across the diaphragm to keep it from creasing.

The oil carries the main burden of the gas pressure; as a result the diaphragm can withstand pressures measured in hundreds of atmospheres. The seal is perfectly tight, for gases as well as for oil. Moreover, the diaphragm is extremely resistant to fatigue in spite of its flimsiness. Its life in a test machine operated at 1,500 revolutions per minute was more than 10,000 hours, or more than a year of service. During that time the diaphragm bent some two billion times.

This invention removed the last barrier to Dros's proposal, and he proceeded to build a prototype of the industrial refrigerator. In its design, because of the rolling diaphragm, it was possible to supplant the displacer by a leakless expansion piston and so to achieve a working space of more suitable shape. This and other details of construction, such as the fairly low operating speed of 600 r.p.m., led us to expect that the machine would have a rather high performance. It exceeded our expectations! At 77 degrees K. it produced about 20 kilowatts of cold, which is to say that it absorbed heat at a rate of 68,000 British thermal units per hour. Its efficiency was 42 percent. This figure is exceptionally high; it far exceeds the performance of our smaller models, which have an efficiency of about 30 percent.

The research that produced the improvements in the Stirling cycle is motivated by the steady increase in applications for refrigeration in the range of temperatures most suited to the Stirling cycle. It is true that these applications were mainly of value in specialized laboratories until about 10 years ago. Recently, however, a spectacular change has occurred and is tending to push cryogenics into industry.

Several examples come to mind. First, cryogenic devices are needed to cool superconductors to the temperatures at which they become superconducting, that is, at which they conduct electricity without resistance. Ordinary "soft" superconductors lose their superconductivity in the presence of a strong magnetic field, but in 1961 "hard" superconductors were discovered that would retain their superconductivity under such conditions; this opened the door to the generation of strong magnetic fields without the usual prohibitive consumption of power [see "Intense Magnetic Fields," by Henry H. Kolm and Arthur J. Freeman, page 66]. Such superconducting magnets are badly needed in magnetohydrodynamic systems and for the development of controlled nuclear fusion. Second, the soft superconductors are finding applications in such devices as the cryotron, which can serve as a tiny logic element in a computer. Third, cryogenic temperatures are also required for masers, parametric amplifiers and infrared detector cells. Finally, low-temperature methods for quickly attaining high and ultrahigh vacuums are becoming practical. For all these applications the availability of reliable refrigerators of all sizes that require little or no attention is imperative.

In such a situation it is natural to wonder whether further improvements in the Stirling cycle can be expected. In many provinces of technology efficiencies of 70 percent are common; such efficiencies have not been reached in refrigeration except for processes using evaporation. Further progress thus cannot be ruled out, particularly when one recalls that the efficiency of the hot-air engine—the other face of the Stirling cycle—is nearly 70 percent. Moreover, the possibilities of the Stirling cycle have prompted numerous investigations of the cycle. As more people become engaged in this work, progress will be faster.

MATHEMATICAL GAMES

The infinite regress in philosophy, literature and mathematical proof

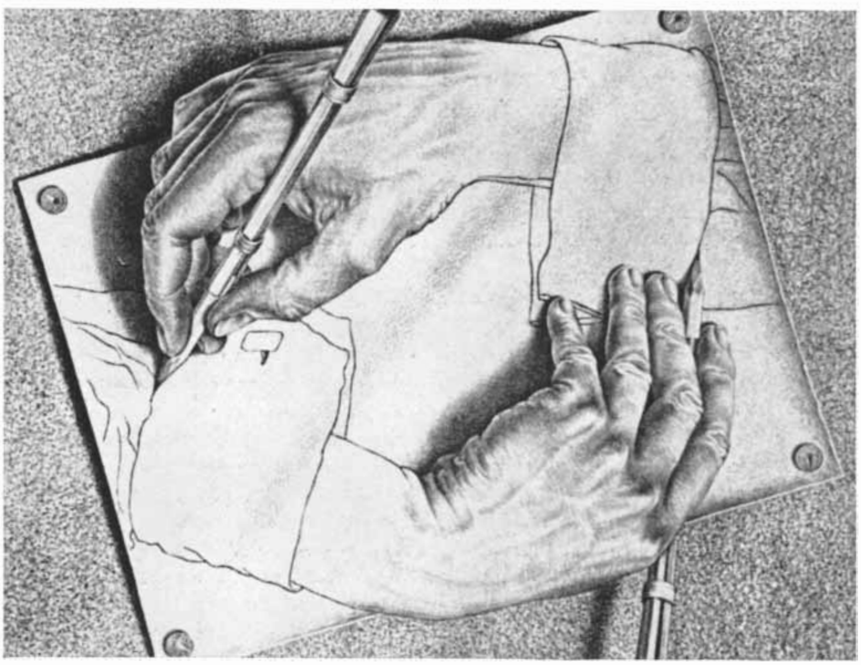
by Martin Gardner

Chairman of a meeting of the Society of Logicians: "Before we put the motion: 'That the motion be now put,' should we not first put the motion: 'That the motion: "That the motion be now put" be now put'?"

—from an old issue of *Punch*

The infinite regress, along which thought is compelled to march backward in a never ending chain of identical steps, has always aroused mixed emotions. Witness the varied reactions of critics to the central symbol of Broadway's most talked-about current play, Edward Albee's *Tiny Alice.* The principal stage setting—the library of an enormous castle owned by Alice, the world's richest woman—is dominated by a scale model of the castle. Inside it lives Tiny Alice. When lights go on and off in the large castle, corresponding lights go on and off in the small one. A fire erupts simultaneously in castle and model. Within the model is a smaller model in which a tinier Alice perhaps lives, and so on down, like a set of nested Chinese boxes.

For many of the play's spectators this endless regress of castles stirs up feelings of anxiety and despair: Existence is a mysterious, impenetrable, ultimately meaningless labyrinth; the regress is an endless corridor that leads nowhere. For theological students, who are said to be flocking to the play, the regress deepens an awareness of what Rudolf Otto, the German theologian, called the *mysterium tremendum:* the ultimate mystery, which one must approach with awe, fascination, humility and a sense of "creaturehood." For the mathematician and the logician the regress has lost most of its terrors; indeed, as we shall soon see, it is a powerful, practical tool even in recreational mathematics. First, however, let us glance at some of the roles it has played in Western thought and letters.



Maurits C. Escher's "Drawing Hands"

Aristotle, taking a cue from Plato's *Parmenides,* used the regress in his famous "third man" criticism of Plato's doctrine of ideas. If all men are alike because they have something in common with Man, the ideal and eternal archetype, how (asked Aristotle) can we explain the fact that one man and Man are alike without assuming another archetype? And will not the same reasoning demand a third, fourth and fifth archetype, and so on into the regress of more and more ideal worlds?

A similar aversion to the infinite regress underlies Aristotle's argument, elaborated by hundreds of later philosophers, that the cosmos must have a first cause. William Paley, an 18th-century English theologian, put it this way: "A chain composed of an infinite number of links can no more support itself than a chain composed of a finite number of links." A finite chain does indeed require support, mathematicians were quick to point out, but in an infinite chain *every* link hangs securely on the one above. The question of what supports the entire series no more arises than the question of what kind of number precedes the infinite regress of negative integers.

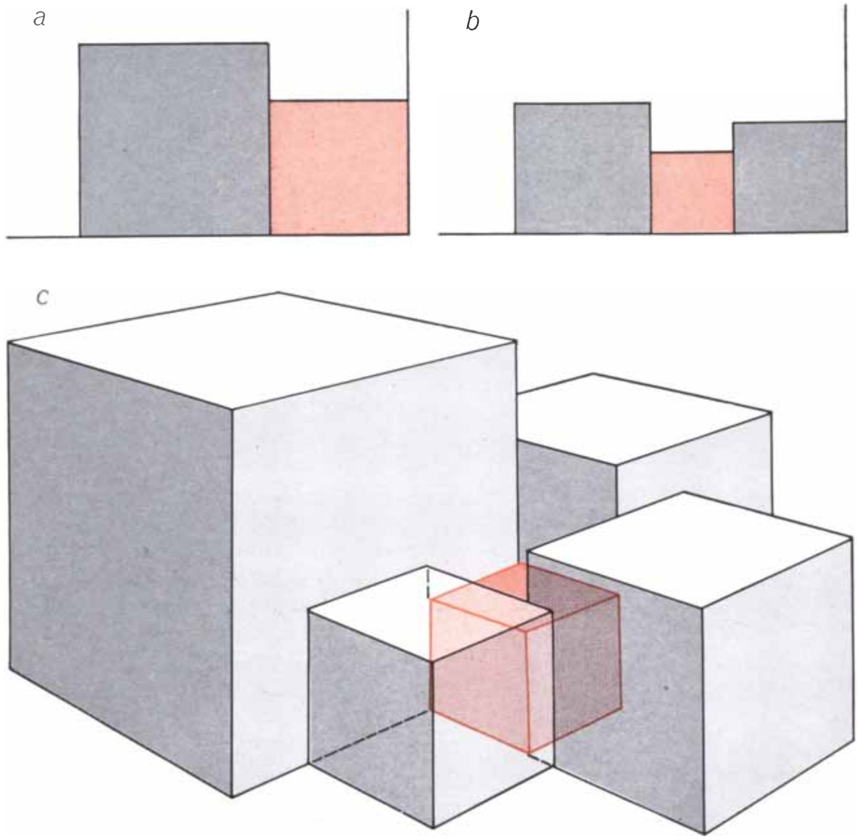
Agrippa, an ancient Greek skeptic, argued that nothing can be proved, even in mathematics, because every proof must be proved valid and its proof must in turn be proved, and so on. The argument is repeated by Lewis Carroll in his paper "What the Tortoise Said to Achilles" (*Mind,* April, 1895). After finishing their famous race, which involved an infinite regress of smaller and smaller distances (see "Mathematical Games" for November, 1964), the Tortoise traps his fellow athlete in a more disturbing regress. He refuses to accept a simple deduction involving a triangle until Achilles has written down an infinite series of hypothetical assumptions, each necessary to make the preceding argument valid.

In recent philosophy the two most revolutionary uses of the regress have been made by the mathematicians Alfred Tarski and Kurt Gödel. Tarski avoids certain troublesome paradoxes in semantics by defining truth in terms of an endless regress of "metalanguages," each capable of discussing the truth and falsity of statements on the next lower level but not on its own level. As Bertrand Russell once explained it: "The man who says 'I am telling a lie of order n' *is* telling a lie, but a lie of order $n + 1$." In a closely related argument Gödel was able to show that there is no single, all-inclusive mathematics but only an infinite regress of richer and richer systems.

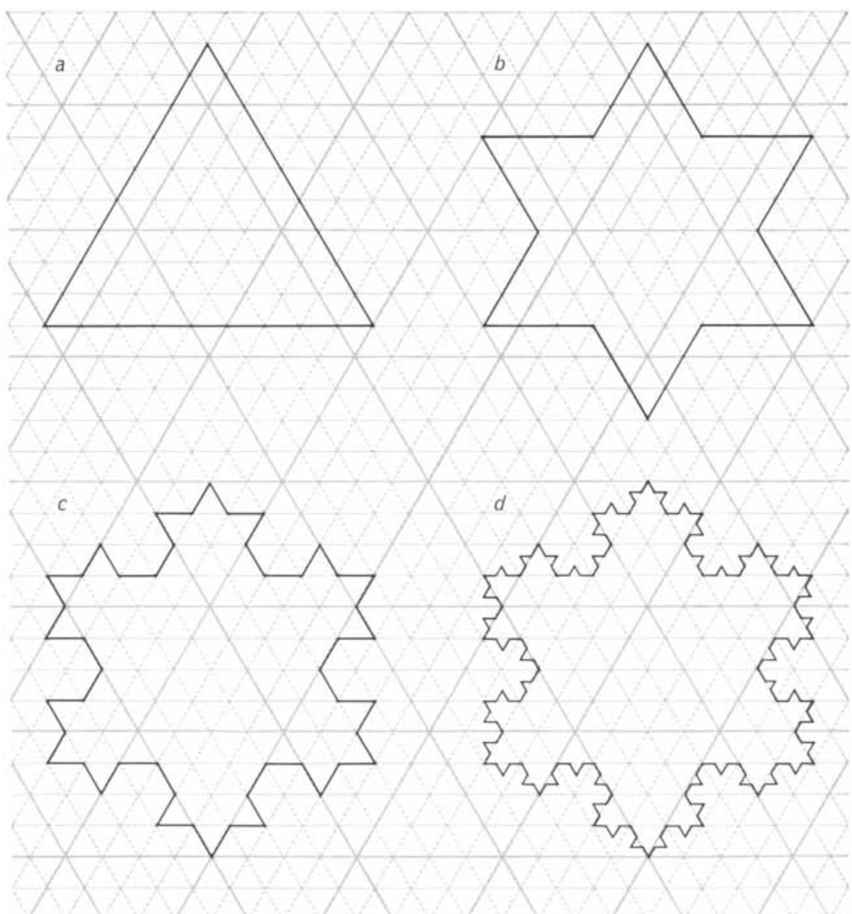
The endless hierarchy of gods implied by so many mythologies and by the child's inevitable question "Who made God?" has appealed to many thinkers. William James closed his *Varieties of Religious Experience* by suggesting that existence includes a collection of many gods, of different degrees of inclusiveness, "with no absolute unity realized in it at all. Thus would a sort of polytheism return upon us. . . ." The notion turns up in unlikely places. Benjamin Franklin, in a quaint little work called *Articles of Belief and Acts of Religion,* wrote: "For I believe that man is not the most perfect being but one, but rather that there are many degrees of beings superior to him." Our prayers, said Franklin, should be directed only to the god of our solar system, the deity closest to us. Many writers have viewed life as a board game in which we are the pieces moved by higher intelligences who in turn are the pieces in a vaster game. The prophet in Lord Dunsany's story "The South Wind" observes the gods striding through the stars, but as he worships them he sees the outstretched hand of a player "enormous over Their heads."

Graphic artists have long enjoyed the infinite regress. Who can look at the striking cover of this issue of *Scientific American* without recalling, from his childhood, a cereal box or magazine cover on which a similar trick was played? The cover of last November's *Punch* showed a magician pulling a rabbit out of a hat. The rabbit in turn is pulling a smaller rabbit out of a smaller hat, and this endless series of rabbits and hats moves up and off the edge of the page. It is not a bad picture of contemporary particle physics. The latest theory proposes a smaller, yet undetected, group of particles called "quarks" to explain the structure of known particles. Is the cosmos itself a particle in some unthinkably vast variety of matter? Are the laws of physics an endless regress of hat tricks?

The play within the play, the puppet show within the puppet show, the story within the story have amused countless writers. Luigi Pirandello's *Six Characters in Search of an Author* is perhaps the best-known stage example. The protagonist in Miguel de Unamuno's novel *Mist,* anticipating his death later in the plot, visits Unamuno to protest and troubles the author with the thought that he too is only the figment of a higher imagination. Philip Quarles, in Aldous Huxley's *Point Counter Point,*



Proof that the cube cannot be "cubed"



The snowflake curve

is writing a novel suspiciously like *Point Counter Point*. Edouard, in André Gide's *The Counterfeiters,* is writing *The Counterfeiters*. Norman Mailer's story "The Notebook" tells of an argument between the writer and his girl friend. As they argue he jots in his notebook an idea for a story that has just come to him. It is, of course, a story about a writer who is arguing with his girl friend when he gets an idea....

J. E. Littlewood, in *A Mathematician's Apology,* recalls the following entry, which won a newspaper prize in Britain for the best piece on the topic: "What would you most like to read on opening the morning paper?"

> OUR SECOND COMPETITION
> The First Prize in the second of this year's competitions goes to Mr. Arthur Robinson, whose witty entry was easily the best of those we received. His choice of what he would like to read on opening his paper was headed "Our Second Competition" and was as follows: "The First Prize in the second of this year's competitions goes to Mr. Arthur Robinson, whose witty entry was easily the best of those we received. His choice of what he would like to read on opening his paper was headed 'Our Second Competition,' but owing to paper restrictions we cannot print all of it."

One way to escape the torturing implications of the endless regress is by the topological trick of joining the two ends to make a circle, not necessarily vicious, like the circle of weary soldiers who rest themselves in a bog by each sitting on the lap of the man behind. Albert Einstein did exactly this when he tried to abolish the endless regress of distance by bending three-dimensional space around to form the hypersurface of a four-dimensional sphere. One can do the same thing with time. There are Eastern religions that view history as an endless recurrence of the same events. In the purest sense one does not even think of cycles following one another, because there is no outside time by which the cycles can be counted; the *same* cycle, the *same* time go around and around. In a similar vein, there is a sketch by the Dutch artist Maurits C. Escher of two hands, each holding a pencil and sketching the other [*see page 128*]. In *Through the Looking-Glass* Alice dreams of the Red King, but the King is himself asleep and, as Tweedledee points out, Alice is only a "sort of thing" in *his* dream. *Finnegans Wake* ends in the middle of a sentence that carries the reader back for its completion to the broken sentence that opens the book.

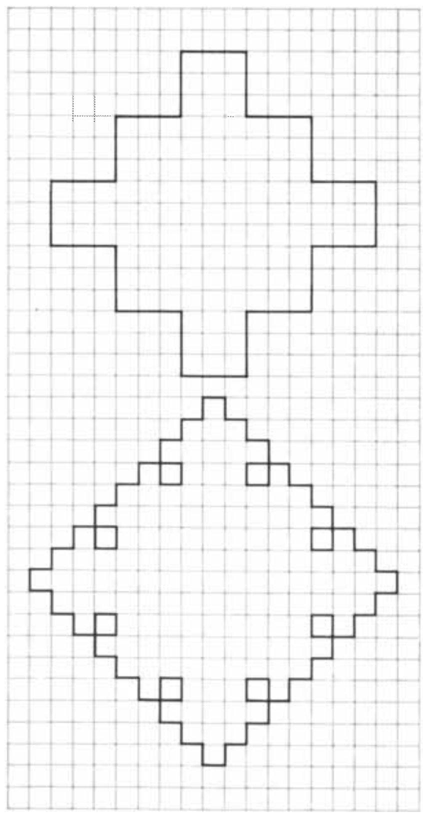
Since Fitz-James O'Brien wrote his pioneer yarn "The Diamond Lens" in 1858 almost countless writers have played with the theme of an infinite regress of worlds on smaller and smaller particles. In Henry Hasse's story "He Who Shrank" a man on a cosmic level much larger than ours is the victim of a scientific experiment that has caused him to shrink. After diminishing through hundreds of subuniverses he lingers just long enough in Cleveland to tell his story before he vanishes again, wondering how long this will go on, hoping that the levels are joined at their ends so that he can get back to his original cosmos.

Even the infinite hierarchy of gods has been bent into a closed curve by Dunsany in his wonderful tale "The Sorrow of Search." One night as the prophet Shaun is observing by starlight the four mountain gods of old—Asgool, Trodath, Skun and Rhoog—he sees the shadowy forms of three larger gods farther up the slope. He leads his disciples up the mountain only to observe, years later, two larger gods seated at the summit, from which they point and mock at the gods below. Shaun takes his followers still higher. Then one night he perceives across the plain an enormous, solitary god looking angrily toward the mountain. Down the mountain and across the plain goes Shaun. While he is carving on rock the story of how his search has ended at last with the discovery of the ultimate god, he sees in the far distance the dim forms of four higher deities. As the reader can guess, they are Asgool, Trodath, Skun and Rhoog.

No branch of mathematics is immune to the infinite regress. Numbers on both sides of zero gallop off to infinity. In modular arithmetics they go around and around. Every infinite series is an infinite regress. The regress underlies the technique of mathematical induction. Georg Cantor's transfinite numbers form an endless hierarchy of richer infinities. A beautiful modern example of how the regress enters into a mathematical proof is related to the difficult problem of dividing a square into other squares no two of which are alike (see "Mathematical Games" for November, 1958). The question arises: Is it possible similarly to cut a cube into a finite number of smaller cubes no two of which are alike? Were it not for the deductive power of the regress, mathematicians might still be searching in vain for ways to do this. The proof of impossibility follows.

Assume that it is possible to "cube the cube." The bottom face of such a dissected cube, as it rests on a table, will necessarily be a "squared square." Consider the smallest square in this pattern. It cannot be a corner square, because a larger square on one side keeps any larger square from bordering the other side [*see "a" in top illustration on preceding page*]. Similarly, the smallest square cannot be elsewhere on the border, between corners, because larger squares on two sides prevent a third larger square from touching the third side [*b*]. The smallest square must therefore be somewhere in the pattern's interior. This in turn requires that the smallest cube touching the table must be surrounded by cubes larger than itself. This is possible [*c*], but it means that four walls must rise above all four sides of the small cube—preventing a larger cube from resting on top of it. Therefore on this smallest cube there must rest a set of smaller cubes, the bottoms of which will form another pattern of squares.

The same argument is now repeated. In the new pattern of squares the smallest square must be somewhere in the interior. On this smallest square must rest the smallest cube, and the little cubes on top of it will form another pattern of squares. Clearly the argu-



The cross-stitch curve

RECENT findings

RESEARCH LABORATORIES

Ford

MOTOR COMPANY

DEFORMATION OF METALS

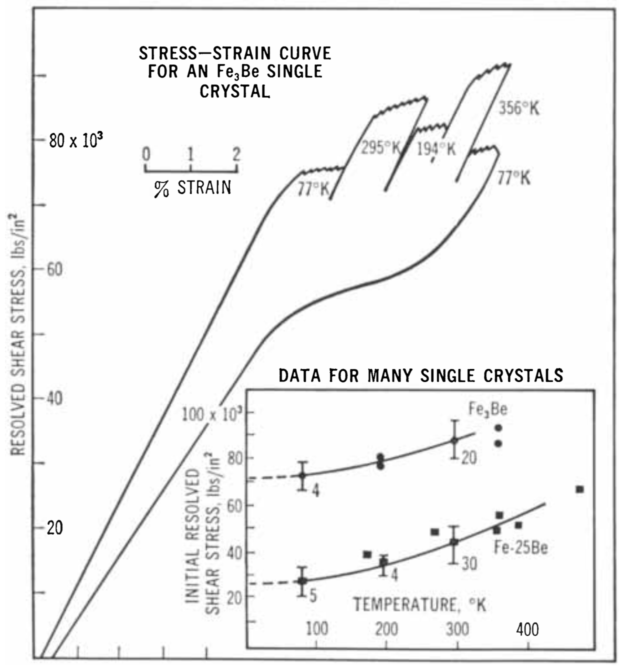
Ford Motor Company scientists identify "continual mechanical twinning" and explore its influence on the plasticity of metals.

Plastic deformation involves the behavior of atomic-scale, line defects called dislocations. At lower temperatures slip (dislocation movement and multiplication) is more difficult, which leads to the common experience that a metal is strong at low temperatures and softens as it is heated. However, some metals also exhibit cooperative movements of many atoms, leading to macroscopic displacements called mechanical twinning. While it has been difficult to separate this phenomenon, it has been long apparent that the overall deformation behavior of a metal can be altered when twinning occurs.

At the Ford Scientific Laboratory, deformation by *continual* mechanical twinning has been identified in single crystals of an iron-beryllium alloy: Fe-25Be (atomic percent). This material behaves oppositely to those which deform exclusively by slip. Its strength *decreases* with decreasing temperature and/or increasing strain rate. These unusual characteristics appear to depend upon a competition between twinning and some slip generated as a consequence of twinning. When slip becomes more difficult (for example, as the temperature is lowered) twinning can dominate the mode of deformation. This viewpoint now has been tested in other metals and alloys and shows that continual mechanical twinning and its characteristics may ensue when slip is inhibited.

An extraordinary tool for study is created by altering the structure of the alloy to the ordered form Fe_3Be (DO_3 superlattice structure). Mechanical twinning of this complex structure leads to an unstable atom arrangement within the twins and involves the storage of extra energy. Thus, Fe_3Be single crystals are remarkable for their high strengths and for their ability to spring back to original shape even after considerable deformation.

This effort to gain a better understanding of the basic behavior of metals is just one of many research projects being conducted by Ford scientists. All have a common aim: greater knowledge which leads to better technology.



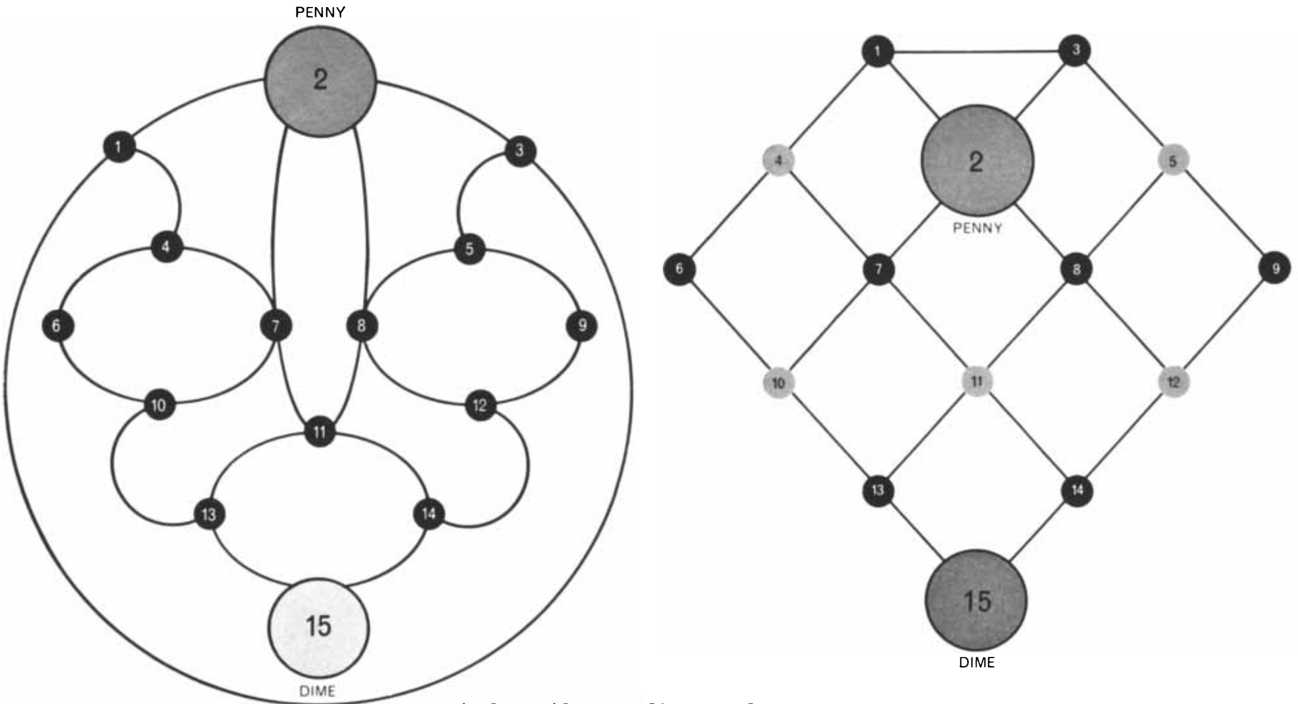
A single crystal of Fe_3Be responding to stress at various temperatures shows the characteristic serrations of continual mechanical twinning, inverse temperature dependence and pseudo-elastic behavior. The inset also shows the inverted relationship between temperature and initial flow stress (compared to metals that deform exclusively by slip) and emphasizes the abnormally high strength of the ordered form.

PROBING DEEPER TO SERVE BETTER

Ford

MOTOR COMPANY

The American Road, Dearborn, Michigan



Analysis of last month's penny-dime game

ment leads to an endless regress of smaller cubes, like the endless hierarchy of fleas in Dean Swift's jingle. This contradicts the original assumption that the problem is solvable.

Geometric constructions such as this one, involving an infinite regress of smaller figures, sometimes lead to startling results. Can a closed curve of infinite length enclose a finite area of, say, one square inch? Such pathological curves are infinite in number. Start with an equilateral triangle [*see "a" in bottom illustration on page 129*] and on the central third of each side erect a smaller equilateral triangle. Erase the base lines and you have a six-pointed star [*b*]. Repeating the construction on each of the star's 12 sides produces a 48-sided polygon [*c*]. The third step is shown in *d*. The limit of this infinite construction, called the snowflake curve, bounds an area 8/5 that of the original triangle. It is easy to show that successive additions of length form an infinite series that diverges; in short, the length of the snowflake's perimeter is infinite. (In 1956 W. Grey Walter, the British physiologist, published a science-fiction novel, *The Curve of the Snowflake,* in which a solid analogue of this crazy curve provides the basis for a time-travel machine!)

Can the reader answer two easy questions about the less well known square version of the snowflake, a curve that has been called the cross-stitch? On the middle third of each side of a unit square erect four smaller squares as shown at the top of the illustration on page 130. The second step is shown at the bottom. (The squares will never overlap, but corners will touch.) If this procedure continues to infinity, how long is the final perimeter? How large an area does it enclose? Both questions will be answered next month.

The answers to last month's collection of short problems follow.

1. Seven is the smallest number of apples that satisfies the conditions of Coleridge's problem.

2. To reverse a man's trousers while his ankles are joined by rope, first slide the trousers off onto the rope, then push one leg through the other. The outside leg is reversed twice in this process, leaving the trousers on the rope right side out but with the legs exchanged and pointing toward the man's feet. Reach into the trousers from the waist and turn both legs inside out. The trousers are now reversed on the rope and in position to be slipped back on the man, zipper in front as originally but with the legs interchanged.

3. In analyzing the topological properties of a network with an unusual pattern it is sometimes helpful to transform the network to a topologically equivalent one that exhibits the network's regularities better. The pattern of the penny-dime game [*at left above*] is readily seen to be equivalent to the board at the right in the illustration. If the penny moves directly toward the dime, it cannot trap it because the dime has what in chess and checkers is called the "opposition." The meaning of this term is brought out by coloring every other spot. As long as both pieces avoid the triangle at the upper right the dime's move will always carry it to a spot of the same color as the spot occupied by the penny; therefore the penny, on its next move, can never catch the dime. To gain the opposition the penny must move once along the line that joins the two colored spots numbered 1 and 3. Because this alters the relative parity of the two pieces it is then a simple matter for the penny to corner the dime.

Translating back to the original board, this means that the penny's best strategy is to move either first to 1, then all around the outside circle to 3, or first to 3 and then around to 1. In either case the penny will then have no difficulty trapping the dime, on spot 6, 9 or 15, before the seventh move.

4. Label the three men *A, B, C* and let *T* stand for truth-teller, *L* for liar and *R* for randomizer. There are six possible permutations of *T, L* and *R:*

	A	B	C
(1)	T	L	R
(2)	T	R	L
(3)	L	R	T
(4)	L	T	R
(5)	R	T	L
(6)	R	L	T

Ask *A* "Is *B* more likely to tell the truth than *C*?" If he answers "Yes,"

Basic Research at Honeywell
Research Center
Hopkins, Minnesota

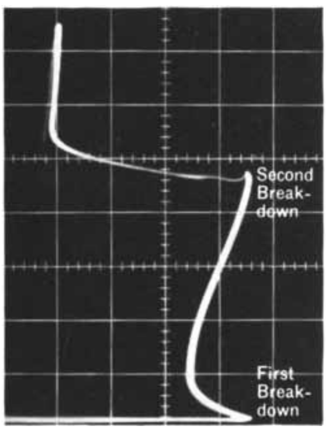
The Problem of Second Breakdown in Transistors

The use of transistors is limited by second breakdown, where there is an abrupt reduction in the collector voltage at levels of current below the rated value. In certain cases this can cause destruction of the transistor. New research indicates there are both thermal and electrical causes and some opportunities to push second breakdown limits considerably higher.

Transistors have a characteristic which is not completely understood and which puts undesirable limits on their use.

In all transistors as the collector-to-emitter voltage (Vce) is increased the transistor will reach a point where the collector current I_c increases rapidly. (See Fig. 1)

I_c



Vce with $I_b = O$

Fig. 1

This occurs at first breakdown and as current increases further, voltage will decrease to a sustaining value. This sustaining value is considered the maximum operating value of the transistor.

As current is further increased, the transistor enters a new mode of operation where voltage decreases rapidly. This is termed the second breakdown region. (See Fig. 1)

Obviously, this phenomenon puts an even lower limit on the device and one that if exceeded is potentially destructive.

Many theories have been proposed to explain this second breakdown but none have been found completely satisfactory.

Honeywell scientists in earlier work on first breakdown developed a technique that is useful in studying second breakdown. They experimentally studied the collector junction, or the interface between the P and N regions, to observe whether breakdown occurs in a uniform manner over the entire collector junction or in localized hot spots at random in the junction.

By introducing a variable transverse base current they literally obtained a "contour map" of the breakdown voltages over the entire collector junction surface. These "maps" show that breakdown voltage is not uniform.

An infrared sensor was used to confirm the non-uniform characteristic. It was observed that the infrared emission was not uniform and in fact at breakdown there was a point of intense local heating.

The results of the mapping technique supported by the infrared observations have led to the development of a model with which to analyze second breakdown.

The model treats a transistor as if it were two discrete devices operated in parallel: one device where second breakdown occurs and one where it has not occurred. It is then possible to compare the devices and come to some conclusions as to what the mechanism is that causes breakdown and triggers the negative resistance phenomena. In general, both electrical and thermal effects are important, with the dominant mechanism determined by the transistor design, mode of operation and imperfections present.

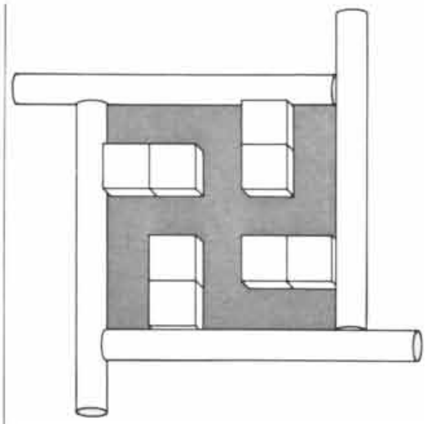
Honeywell scientists have concluded that second breakdown in transistors originates in majority carrier current (electron current in a PNP transistor) from the breakdown spot. These majority carriers are generated by the process of avalanche multiplication. During multiplication at the breakdown spot an equal number of electrons and holes are produced. In a PNP transistor the holes enter the collector and the electrons flow through the base region to recombine with holes lost by the emitter. This electron flow has a transverse component which causes a voltage drop which concentrates the emitter current in the vicinity of the breakdown spot. The higher emitter current to the breakdown spot results in a higher electron current through the base. Thus the cycle is regenerative and if the process continues, it will result in the hot spot mentioned earlier.

Continuing work should lead to a computer program to solve equations to predict where and when breakdown will occur and whether by electrical or thermal mechanisms.

The result, it is hoped, would be the ability to design transistors to minimize thermal effects and to eliminate or minimize the electrical effects.

If you are engaged in research on second breakdown you are invited to correspond with Mr. Harold Josephs, Honeywell Research Center, Hopkins, Minnesota. If you are interested in a career at Honeywell's Research Center and hold an advanced degree, write to Dr. John Dempsey, Director of Research at this same address.

Honeywell



Solution of swastika puzzle

lines 1 and 4 are eliminated and you know that C is not the randomizer. If he answers "No," lines 2 and 3 are eliminated and you know that B is not the randomizer. In either case, turn to the man who is not the randomizer and ask any question for which you both know the answer. For example: "Are you the randomizer?" His answer will establish whether he is the truth-teller or the liar. Knowing this, you can ask him if a certain one of his companions is the randomizer. His answer will establish the identities of the other two men. There are alternate solutions along similar lines.

5. When James Ferguson's curious mechanical device is turned clockwise, wheel C rotates clockwise in relation to the observer, D rotates counterclockwise and E does not rotate at all!

6. Four cigarettes and eight sugar cubes can be placed on a dark surface to form an excellent replica of a Nazi swastika, as shown above.

7. What is the probability of forming one ring by a random joining of pairs of upper ends of six blades of grass, followed by a random joining of pairs of lower ends? Regardless of how the upper ends are joined, we can always arrange the blades as shown on the opposite page. We now have only to determine the probability that a random pairing of lower ends will make a ring.

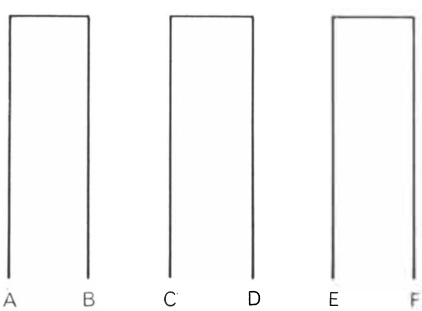
If end A is joined to B, the final outcome cannot be one large ring. If, however, it is joined to C, D, E or F, the ring remains possible. There is therefore a probability of 4/5 that the first join will not be disastrous. Assume that A is joined to C. B may now join D, E or F. Only D is fatal. The probability is 2/3 that it will join E or F, and in either case the remaining pair of ends must complete the large ring. The same would hold if A had been joined to D,

E or F instead of to C. Therefore the probability of completing the ring is $4/5 \times 2/3 = 8/15 = .53+$. That the probability is better than half is somewhat unexpected. This means that in the pencil-and-paper version explained last month the second player has a slight advantage. Since most people would expect the contrary, it makes a sneaky game to propose for deciding who picks up the tab. Of course you generously allow your companion to play first.

The problem generalizes easily. For two blades of grass the probability is 1 (certain), for four blades it is $2/3$, for six (as we have seen) it is $2/3 \times 4/5$, and for eight blades, $2/3 \times 4/5 \times 6/7$. For each additional pair of blades simply add another fraction. It is easy to determine the next fraction because the numerators of this series are the even numbers in sequence and the denominators are the odd numbers in sequence! For a derivation of this simple formula, and the use of Stirling's formula to approximate the probability when very large numbers of fractions must be multiplied, see *Challenging Mathematical Problems with Elementary Solutions, Vol. I,* by the Russian twin brothers A. M. and I. M. Yaglom. (It is problem No. 78 in the English translation published in 1964 by Holden-Day, Inc.)

8. The Mudville team could have scored as few as no runs at all even though Casey, the lead-off man, came to bat every inning. In the first inning Casey and the next two batters walk and the next three strike out. In the second inning the first three men walk again, which brings Casey back to bat. But each runner is caught off base by the pitcher, so Casey is back at the plate at the start of the third inning. This pattern is now repeated until the game ends with no joy in Mudville, even though the mighty Casey never once strikes out.

9. In May or June I shall report on the best solutions received from readers who worked on the sliding-block puzzle.



The blades-of-grass problem

THE AMATEUR SCIENTIST

How the amateur can identify subatomic particles from their tracks in photographs

Conducted by C. L. Stong

About 20 of the almost 100 different subatomic particles that constitute the building blocks of the universe make visible trails when they move at high velocity in a detecting apparatus such as a cloud chamber or bubble chamber. The trails all look much alike to the casual observer; they are silvery filaments in seemingly random array. A few may appear thicker or thinner than most. Some may curve to the right or left, but most are nearly straight. An occasional track may extend in a straight line for some distance and then abruptly terminate in a hook or a branching configuration.

How does the physicist untangle the maze and identify each of the interacting particles? Several analytical techniques have been developed for recognizing specific particles by the pattern of their trails. Some of the techniques are almost as complex as the puzzles they are designed to solve. A few, however, can be grasped by amateurs. One simple technique was devised independently last year by Eric M. Dulberg, who was then a student at Benjamin Franklin Senior High School in New Orleans and now attends the Stevens Institute of Technology in Hoboken, N.J. For this accomplishment he received one of the top awards at the National Science Fair and another award from the Atomic Energy Commission. Dulberg's technique can be used to identify any particle that generates a distinctive trail in a single photograph, as well as some particles that make no trails. The method will not identify the so-called resonance particles, however, because their presence must be established by the statistical analysis of hundreds of photographs.

Dulberg writes: "To identify the particles involved in a nuclear interaction by the technique I use, certain information must be available in addition to that provided by the photograph of the interaction. One must know the kind of particle that initiates the interaction, its kinetic energy, the strength of the magnetic field in which it moves and the target particle with which it reacts by means of the nuclear, or 'strong,' force. This information is always available to those who perform nuclear experiments because known particles such as protons, electrons and mesons are deliberately accelerated to prescribed energies for use as projectiles against known target particles. Typically the target particles are protons, represented by the nuclei of hydrogen atoms. In addition one must be familiar with certain details that distinguish each particle from all others, such as its characteristic mass, electric charge (if any), the 'spin' of the particle and the kinds of particles into which it decays. All these characteristics have been tabulated.

"The analysis of track patterns obviously becomes easier with practice. One learns to recognize the trails of certain particles. As the characteristics of the particles become increasingly familiar the analysis takes on some of the aspects of an art.

"I first examine the photograph of the nuclear event, make a pencil sketch of the significant interaction and, by reference to the known characteristics of the particles, establish a tentative identification. This guess is then checked by comparing the behavior of the assumed particles with that required by the conservation laws that all particles obey. If all the observed particles obey these laws, my tentative identification is accepted as final; otherwise I try again. If all the particles but one appear to obey the laws, and this one would obey them also if it were endowed with certain characteristics, the possibility exists that the exception is an unknown particle. Here the technique can serve to predict the essential characteristics of the unknown particle.

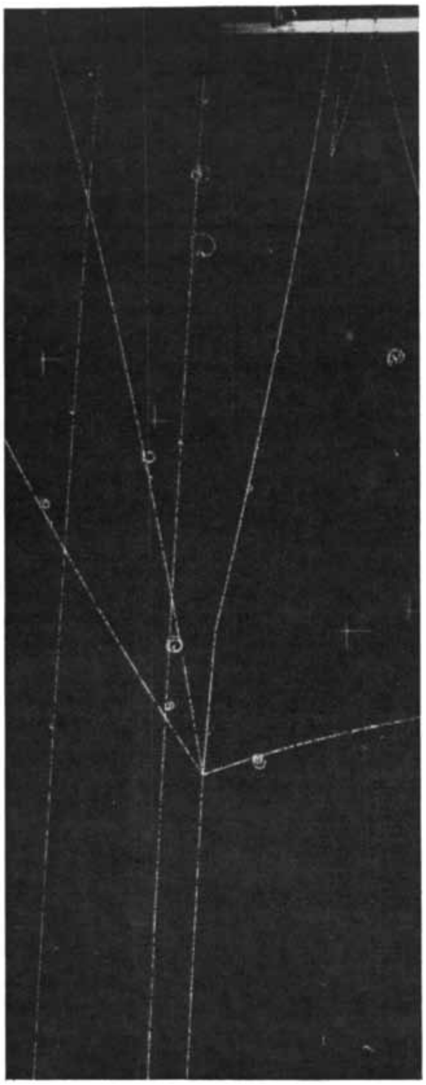
PARTICLES (MULTIPLETS)	SYMBOL	CHARGE STATES	SPIN	STRANGENESS	REST MASS	PARITY	BARYON NUMBER
PION	π	+, −, 0	0	0	137	−1	0
K MESON	K	+, 0	0	+1	496	−1	0
NUCLEON	n p	+, 0	±½	0	939	+1	+1
LAMBDA HYPERON	Λ	0	±½	−1	1,115	+1	+1
SIGMA HYPERON	Σ	+, −, 0	±½	−1	1,193	+1	+1
XI HYPERON	Ξ	−, 0	±½	−2	1,318	+1	+1
OMEGA	Ω	−	±½	−3	1,676	+1	+1

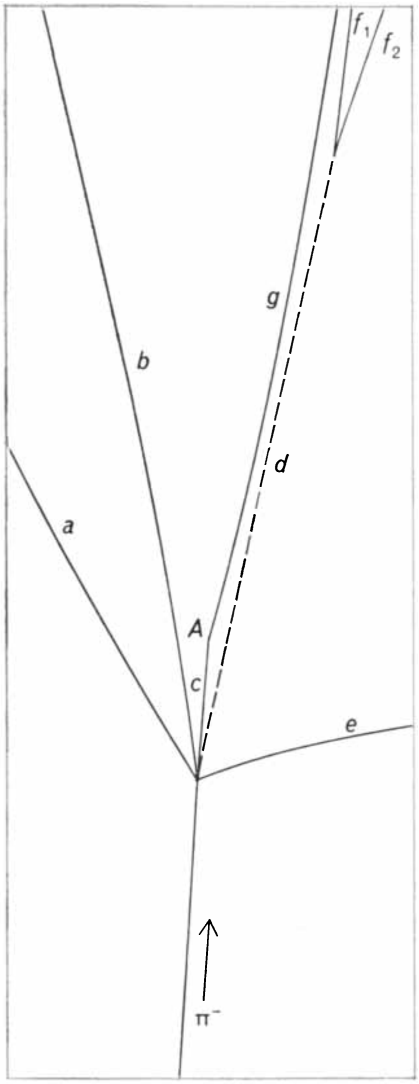
Characteristics of subatomic particles

PARTICLES	DECAY MODES						LIFETIME
ν	STABLE						STABLE
$\bar{\nu}$	STABLE						STABLE
e^-	STABLE						STABLE
e^+	STABLE						STABLE
μ^-	$e^- + \nu + \bar{\nu}$						2.2×10^{-6}
μ^+	$e^+ + \bar{\nu} + \nu$						2.2×10^{-6}
π^0	$\gamma + \gamma$	$\gamma + e^+ + e^-$					2.3×10^{-16}
π^-	$\mu^- + \bar{\nu}$	$e^- + \bar{\nu}$ *					2.6×10^{-8}
π^+	$\mu + \nu$	$e^+ + \nu$ *					2.6×10^{-8}
K_1^0	$\pi^+ + \pi^-$	$2\pi^0$					1×10^{-10}
K^-	$\mu^- + \bar{\nu}$	$\pi^- + \pi^0$	$2\pi^- + \pi^+$	$\pi^- + 2\pi^0$	$\mu^- + \bar{\nu} + \pi^0$	$e^- + \bar{\nu} + \pi^0$	1×10^{-10}
K^+	$\pi^0 + e^+ + \nu$	$\pi^0 + \mu^+ + \nu$	$\mu^+ + \nu$	$\pi^+ + \pi^0$	$2\pi^+ + \pi^-$	$\pi^+ + 2\pi^0$	1.2×10^{-8}
$\bar{K}_2^0$	$\pi^+ + \pi^- + \pi^0$	$3\pi^0$	$\pi^+ + \mu^- + \bar{\nu}$	$\pi^- + \bar{\mu}^+ + \nu$	$\pi^+ + e^- + \bar{\nu}$	$\pi^- + \bar{e}^+ + \nu$	$\sim 6 \times 10^{-8}$
Ξ^0	$\Lambda^0 + \pi^0$						1.5×10^{-10}
Ξ^-	$\Lambda^0 + \pi^-$						1.3×10^{-10}
$\bar{\Xi}^0$	$\bar{\Lambda}^0 + \pi^0$						1.5×10^{-10}
$\bar{\Xi}^-$	$\bar{\Lambda}^0 + \pi^+$						1.3×10^{-10}
Σ^0	$\Lambda^0 + \gamma$						$< 10^{-12}$
Σ^-	$n^0 + \pi^-$	$n^0 + e^- + \bar{\nu}$ *	$n^0 + \mu^- + \bar{\nu}$ *				1.7×10^{-10}
Σ^+	$p^+ + \pi^0$	$n^0 + \pi^+$	$n^0 + e^+ + \nu$ *	$n^0 + \mu^+ + \nu$ *			$.8 \times 10^{-10}$
$\bar{\Sigma}^0$	$\Lambda^0 + \gamma$						$< 10^{-12}$
$\bar{\Sigma}^-$	$\bar{p} + \pi^0$	$\bar{n}^0 + \pi^-$	$\bar{n}^0 + e^- + \bar{\nu}$ *	$\bar{n}^0 + \mu^- + \bar{\nu}$ *			1.7×10^{-12}
$\bar{\Sigma}^+$	$\bar{n}^0 + \pi^+$	$\bar{n}^0 + e^+ + \nu$ *	$\bar{n}^0 + \mu^+ + \nu$ *				$.8 \times 10^{-10}$
Λ^0	$p^+ + \pi^-$	$n^0 + \pi^0$	$p^+ + e^- + \bar{\nu}$ *	$p^+ + \mu^- + \bar{\nu}$			2.5×10^{-10}
$\bar{\Lambda}^0$	$\bar{p}^- + \pi^+$						2.5×10^{-10}
n^0	$p + e^- + \bar{\nu}$						1.01×10^3
$\bar{n}^0$	$\bar{p} + e^+ + \nu$						1.01×10^3
$p, \bar{p}$	STABLE						STABLE
Ω^-	$\Xi^0 + \pi^-$	$\Lambda^0 + K^-$	$\Xi + \pi^0$				
Ω^+	?						

NOTE: UNLISTED ANTIPARTICLES DECAY INTO ANTIPARTICLES OF THE DECAY PRODUCTS.

Characteristics of some decay particles (asterisks denote rarity)





MAGNETIC FIELD 17,000 GAUSS KINETIC ENERGY 5 BEV
INCOMING PARTICLE π^- TARGET PARTICLE p

Example of identification procedure

"It is rarely necessary or even possible for the amateur to apply all eight of the known conservation laws to a given interaction. The law of parity conservation, for example, can be applied only if the investigator has access to many different photographs of the interaction. Fortunately most of the analyses for which the technique is appropriate can be confirmed adequately by reference to only a few of the laws. They include the conservation of linear momentum, charge, mass and energy, angular momentum (spin), baryon number, lepton number and strangeness.

"Linear momentum is conserved in a nuclear interaction if the product of the mass and the velocity vector of the impinging particles is equal to the sum of the products of the mass and the velocity vector of each of the product particles that emerge from the interaction. Momentum must be neither gained nor lost as a result of the interaction. Similarly, electric charge must be conserved. When two particles interact, the sum of the charges of the participating particles must remain constant. For example, assume that the symbol Q represents charge in an interaction that involves a particle a that carries a charge of $+Q$ and a particle b with a charge of $-Q$. If three particles emerge from the interaction, one with a charge of $+Q$ and another with a charge of $-Q$, the law of conservation of charge requires that the third product particle must be electrically neutral. The total mass and energy of the reacting particles must also equal the total mass and energy of the product particles.

"Spin is found by multiplying the quantity $h/2\pi$ by a constant, in which π is 3.1416 and h is Planck's constant (6.62×10^{-27} erg second). Depending on the particle, spin can have a value of $\pm 1/2$, $\pm 3/2$, $\pm 5/2$ and so on, or of 0, ± 1, ± 2, ± 3 and so on. Spin is conserved if the total spin of the reacting particles equals that of the product particles.

"Baryons, which are the particles of greatest mass, and leptons, which are the particles of least mass, must also be conserved. Each baryon is assigned the baryon number $+1$; its antiparticle, -1. Leptons are assigned similar lepton numbers. Baryons and leptons are separately conserved if the sum of their respective baryon and lepton numbers remains unchanged following an interaction.

"The term 'strangeness' came into physics during the past decade as a result of the observation that some particles are formed by interactions that involve the strong nuclear force but decay in processes that involve another force: the 'weak' force. This was a form of behavior then considered strange, and it led to the discovery of a new conservation law. In mathematical terms strangeness is denoted by S and is equal to twice the average charge assigned to a particle minus its baryon number. The average charge of a particle is equal to the charge of the group of particles of which it is a member, divided by the number of particles constituting the group. The nucleons, for example, are a group of two particles: the proton of charge $+1$ and the neutron of charge 0. The charge of the group is $+1$, and the average charge of the proton and neutron is $+1/2$. Hence the proton is not strange because its average charge, $\overline{Q}$, equals $+1/2$ and its baryon number equals $+1$. Putting these numbers into the formula, one obtains $2(1/2) - (+1)$ and finds that the proton's strangeness is 0. Strangeness is conserved when the sum of the strangeness values of the reacting particles equals the sum of the strangeness values of the product particles.

"During the course of an analysis the conservation laws can frequently provide clues to the characteristics of a particle that is being sought to explain a trail. The lifetime of an unstable particle—the interval during which it exists before decaying—can also be usefully taken into account during an analysis. In general, particles that have a short lifetime make short trails compared with the trails of particles that have a long lifetime.

"The system of nomenclature I use

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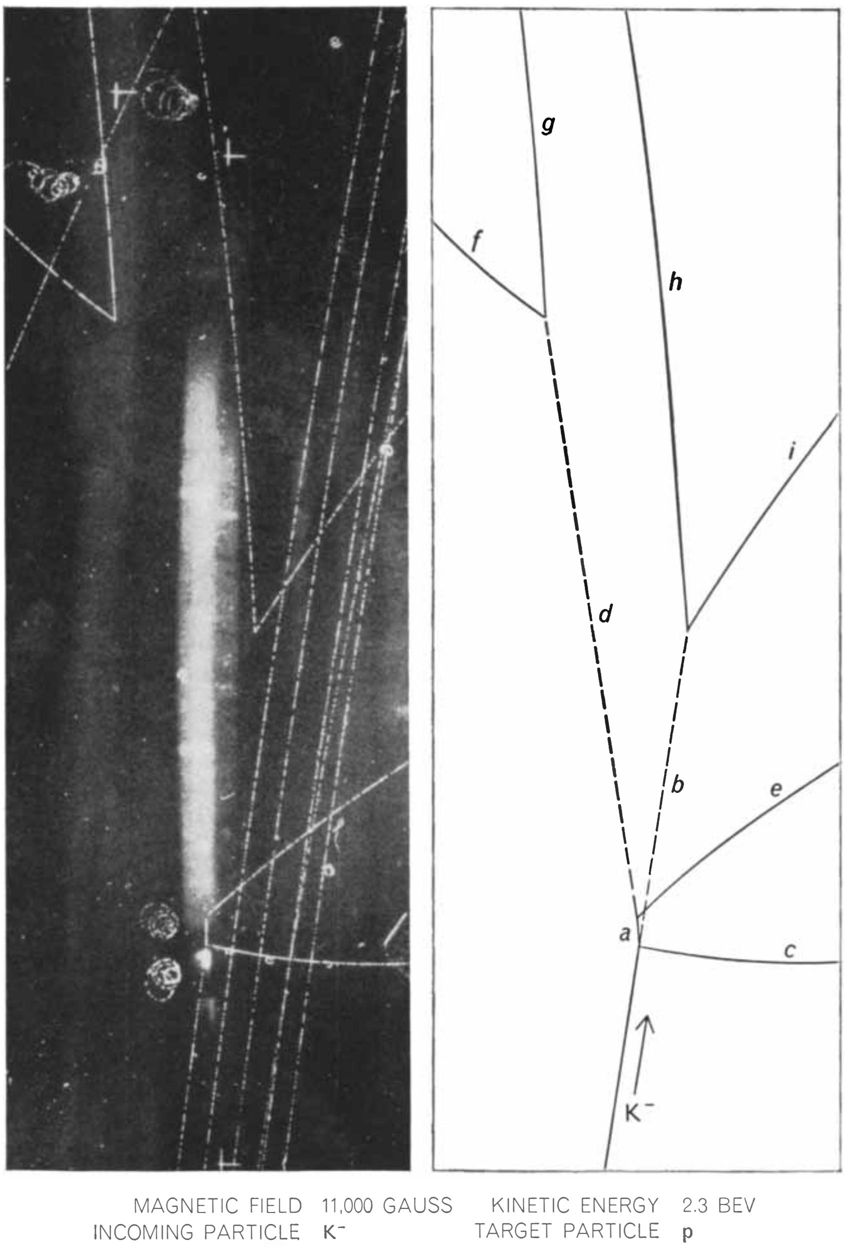
has now been replaced by a new system that classifies particles by groups. In this discussion, however, the old system will be used and should lead to no confusion. The inventory includes 36 particles. Those of greatest mass include 16 baryons and antibaryons—among them the xi (Ξ), sigma (Σ) and lambda (Λ) particles—and the nucleons. Seven particles of intermediate mass are classed as mesons in two groups, the *K* particles and pi (π) particles. The eight leptons, the particles of least mass, include the electron (e), the muons (μ) and the neutrinos (ν). Finally, there is one massless boson, the photon (γ). The characteristics of these particles and the product particles into which some of them decay are presented in the accompanying tables [*pages 136 and 137*].

"The trails of any of these particles may appear in cloud chambers of the kind that amateurs can construct, but practically all of them are made by electrons, protons and pi particles. I experimented with a number of homemade chambers, detecting mostly electrons and alpha particles (helium nuclei) when the source was radium and mostly protons and pi particles when the source was cosmic radiation.

"These tracks are easily identified by inspection. Alpha particles from a radium source make trails about an inch long that occasionally end in a small hook. The trails of electrons are thin and wavy. The trails of some cosmic rays (protons, mesons and electrons) appear as relatively straight lines of intermediate thickness that frequently extend across the chamber. Some, however, may leave wavy or spiraling trails. Their appearance depends somewhat on the angle of view. In a chamber equipped with a viewing window at the top the trails of cosmic rays may be a row of dots if the particles enter the chamber directly from above, or straight lines if they enter obliquely. If the chamber is equipped with an appropriate magnetic field, the velocity and energy of the particles can be computed by the methods discussed in this department for June, 1959.

"The photographs of nuclear interactions that I have analyzed were obtained from the Brookhaven National Laboratory, along with the identity of the impinging particle, its kinetic energy, the strength of the magnetic field and the target particle, which I assume to be a proton at rest. All the trails must lie approximately in the plane of the photographic paper. I first make a drawing of the interaction, as shown in the accompanying illustration [*page 138*]. The path of the incoming particle is labeled with the symbol of the known particle, which in the example illustrated is a π^- meson with a kinetic energy of five billion electron volts. The trails of the product particles are next labeled serially with lowercase letters: *a*, *b*, *c* and so on. In addition I occasionally identify with a capital letter the point at which a trail makes an abrupt angle. Such bends indicate points at which particle decays occur. For example, a particle may decay into another charged particle and an uncharged one that does not make a trail. Such an interaction is indicated at point *A* in the illustration.

"It is apparent in this example that the entering π^- meson interacted with a proton to yield at least four and possibly five product particles, here labeled *a*, *b*, *c*, *d* and *e*. Observe that an extension of the line that bisects the angle made by the diverging trails f_1 and f_2 would intercept the trail of the π^- particle at the point where the interaction occurred. Neither f_1 nor f_2 is curved appreciably, even though each is the trail of a charged particle moving in a relatively strong magnetic field of 17,000 gauss. The fact that the particles make trails proves that they carry charges. The fact that they do not curve much in spite of the magnetic field means that they must be particles of comparatively high mass or energy. It

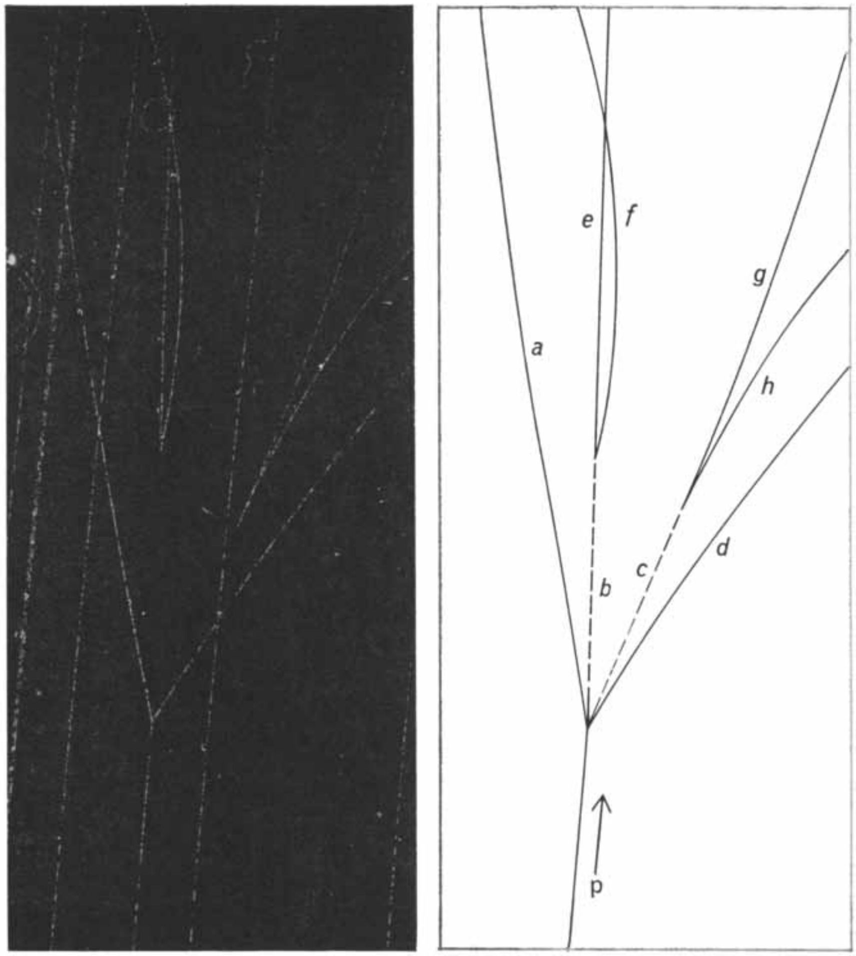


More tracks identified

Marcel Griaule, Musée de l'Homme

Aero Service Corporation

E. Vogel, Musée de l'Homm



MAGNETIC FIELD 7,000 GAUSS KINETIC ENERGY 2.85 BEV
INCOMING PARTICLE p TARGET PARTICLE p

A test for the reader

is also apparent that the kinetic energies of the two particles must be approximately equal, because the trails diverge at approximately equal angles from the point of origin. The particles must likewise be equal in mass, because they follow complementary paths. It can be tentatively concluded, therefore, that f_1 and f_2 are particles of the same type but of opposite charge, because particles of the same kinetic energy and mass are by definition of the same type. That they are oppositely charged is established by the fact that particle *d*, which decays into f_1 and f_2, has no charge. Thus f_1 and f_2 must be oppositely charged to conserve charge.

"The second table [*page 137*] lists only one decay that yields two particles of the same type but of opposite charge: the $K_1{}^0$ meson. It can be assumed with reasonable confidence that the interaction involved the $K_1{}^0$ meson because (1) this uncharged particle would have made no trail and (2) charge is conserved in the decay. The assumption can now be made that f_1 is a π^+ meson and f_2 a π^- meson. The sign of the particles is established by first observing the direction of curvature of any electrons in the photograph. Electrons of low energy characteristically appear as tightly spiraled coils in almost all photographs of nuclear interactions. Those in this photograph spiral in a clockwise direction. The electron carries a negative charge. The particle f_2 also curves in a clockwise direction and so must be the negatively charged meson of the pair.

"Track *c* curves gently in a counterclockwise direction and accordingly must carry a positive charge. It must also be a fairly massive particle, because its path does not curve appreciably or change direction sharply as might be expected of a particle of low mass and momentum. The photograph shows that particle c decays into a positively charged product and at least one neutral particle, the latter fact being evident in the changed direction of the trail. It is also apparent that the kinetic energy of c must be medium or even low, because it is a relatively heavy particle that manages to curve slightly. The positive particle into which c decays must also be heavy and of low kinetic energy for the same reasons. In addition it is apparent that particle g is stable, because it continues on its way for a considerable distance without decaying. The only known stable particle that carries a positive charge is a proton. Particle g is tentatively so identified. The particle that decayed at point A yielded a proton and an uncharged particle. Only one particle is listed in the table with this mode of decay: the positive sigma particle Σ^+. The uncharged particle must therefore be a π^0 meson.

"At this point a check can be made to ascertain if strangeness has been conserved by the assumed particles. Reference to the table of characteristics shows that the strangeness of the reacting particle π^- is 0. The proton with which it interacted also has a strangeness of 0, so the strangeness of the original event is 0. The sum of the strangeness of the assumed Σ^+ and $K_1{}^0$ particles is also 0 (S of $\Sigma^+ = -1$, S of $K_1{}^0 = +1$). Strangeness is conserved so far.

"The law of the conservation of baryons can now provide a clue to the identity of the remaining unknown particles. The reaction at this stage can be expressed symbolically: $\pi^- + p \rightarrow a + b + c + \Sigma^+ + K_1{}^0 + e$, in which a, b, c and e are the unknowns. Substituting the baryon numbers, as listed in the table, for the tentatively identified particles alters the equation to the form $0 + 1 \rightarrow a + b + c + 1 + 0 + e$. The sum of the baryon numbers of a, b, c and e must therefore be 0, because the sum of the reactants is 1 and the sum of the product particles is also 1 without taking a, b, c and e into account. Can any of these be baryons? For the conservation of baryons two of the three particles a, b and c would have to constitute a baryon-antibaryon pair. The particle that made track e cannot be a baryon because the angle between e and the path of the original π^- is so large that momentum could not be conserved if the particle were a baryon. Much the same kind of reasoning leads to the conclusion that a and b cannot be baryons: their energies in this case (the sum of the individual products of their masses multiplied by their kinetic energy) together with the momentum of the other product particles would exceed that of the reacting particles. Thus they must be mesons, the only other class of particles that participate in the strong interaction.

"Two types of meson are known, π and K. Which of these might be the unknowns? K mesons have a strangeness number of $+1$ and a mass equivalent to approximately 496 million electron volts (mev); π mesons have a strangeness of 0 and a mass of approximately 137 mev. The strangeness of the reacting particles is 0. Hence for strangeness and total energy to be conserved the unknown particles must be π mesons. The charges of a and e are negative because these unknowns curve in a clockwise direction; b must carry a positive charge because it curves in the opposite direction. The complete interaction can be expressed in the symbolic form $\pi^- + p \rightarrow \pi^- + \pi^+ + \Sigma^+ + K_1{}^0 + \pi^-$, followed by the secondary decays $\Sigma^+ \rightarrow p + \pi^0$ and $K_1{}^0 \rightarrow \pi^+ + \pi^-$. The characteristics of the particles can then be written in the same sequence for a check against the conservation laws. Beginning with the charge of the particles the equation for the conservation of charge would be: $(-1) + 1 = (-1) + 1 + 1 + 0 + (-1)$. The equation balances; charge is conserved. When expressed in terms of baryon numbers, the equation also balances: $0 + 1 = 0 + 0 + 1 + 0 + 0$. It also does for spin: $0 + (\pm 1/2) = 0 + 0 + (\pm 1/2) + 0 + 0$. Finally, it also balances for strangeness: $0 + 0 = 0 + 0 + (-1) + 1 + 0$. In the case of the decay $K_1{}^0 \rightarrow \pi^+ + \pi^-$, the equation takes this form to express conservation of charge: $0 = 1 + (-1)$; baryons, $0 = 0 + 0$; spin, $0 = 0 + 0$. $K_1{}^0$ has a strangeness of 1, which means that $K_1{}^0$ is a strange particle. (That is the case with any particle having a strangeness number other than 0.) Strangeness is not conserved in the decay of strange particles. Accordingly the equation for strangeness of the $K_1{}^0$ decay does not balance.

"Useful deductions can be made merely by inspecting the trails of a more complex reaction such as the one depicted by the second accompanying photograph and its associated drawing [*page 140*]. A K^- meson (the antiparticle of K^+) interacts with a proton in the bubble chamber. The short, straight trail a must have been made by either a massive particle or one of high kinetic energy. Certainly its momentum is much greater than the particle responsible for trail c because the latter particle makes a large angle with respect to the trail of the incoming K^- meson. Assume that trail *a* was made by a relatively massive particle. It decays into the particle responsible for trail *e* that curves in a clockwise direction, indicating negative charge. The conservation of linear momentum for the decay of *a* would require a neutral particle as a product of the decay. The only heavy, unstable particles that carry negative charge are Ξ^-, Σ^- and $\overline{\Sigma}^-$. One of these must be responsible for *a*.

"Alternatively it can be assumed that the particle responsible for trail *a* does not decay into *d* and *e* but rather into a particle of zero charge *j* and *e*. In this event *j* might be a neutron (or antineutron) because it is not seen to decay. (The lifetime of a neutron is about 1,000 seconds.) The unknown *a* might then be assumed to be a $\overline{\Sigma}^-$ that would decay into an antineutron and a π^-, or a Σ^- that would decay into a neutron and a π^-. A simple computation quickly demonstrates that the energy of the reacting particles is not adequate to balance the energy that would be represented by this array of postulated particles. The law of energy conservation would not support the assumption.

"Trail *a* must have been made by a Ξ^-. This particle decays into a π^- and a Λ^0, which in turn decays into a proton and a π^-. The particle that made trail *f* moved in a clockwise direction and therefore carried a negative charge. Trail *g* was made by a particle that moved in a counterclockwise direction and so carried a positive charge. The curvature of this trail is substantially less than that of trail *f*, indicating that the responsible particle is the more massive of the pair. For these reasons the particles that made trails *f* and *g* can be tentatively designated as a π^- meson and a proton because these are the decay products of Λ^0. The particle that made trail *e* can now be designated as π^- because this meson is the companion of Λ^0 in the Ξ^- decay.

"Still other clues to the identity of particles can be developed by reference to the conservation laws. For example, the table indicates a strangeness of -1 for the anti-*K* particle and a strangeness of 0 for the proton. Their sum is -1. Similarly, the sum of the baryon products is 1, the baryon number of the reacting particles. The reaction at this point in the analysis can be written symbolically in the form $K^- + p \rightarrow \Xi^- + x^0 + y^+$, in which x^0 is an unknown particle of zero charge and y^+ an unknown of positive charge. (It can be demonstrated, as in the case of the assumed $\overline{\Sigma}^-$ previously discussed, that a second particle of zero charge cannot exist in this interaction.) It can be assumed that x^0 and y^+ are products of the initial interaction involving K^- and its target proton because other product particles have already accounted nicely for the decay of Ξ^-. In other words, the neutral particle x^0 must have originated in the initial interaction and decayed into the particles responsible for trails *h* and *i*. Trail *c* must have been made by a positively charged particle of low mass because it curves counterclockwise and makes a large angle with respect to the trail of K^-. In the case of a massive particle this abrupt change in direction would imply more energy than is available in the system, and such a situation would violate the law of the conservation of momentum. Thus the particle is not a baryon, which is heavy. This interaction involved the strong nuclear force, the type of interaction in which leptons do not participate. For this reason x^0 and y^+ cannot be leptons. The only remaining particle type is the meson. Assume that x^0 and y^+ are mesons, either of the *K* or π types. *K* is relatively massive, according to the table. Assume that y^+ is π^+ since y^+ has a small mass. The conservation laws are useful for predicting the characteristics of unknown particles and can now be used for developing a clue to the identity of x^0. Strangeness, for example, must be conserved. The strangeness of the reacting particles is -1 (because that of K^-, the antiparticle, is -1 and that of the proton is 0). The strangeness of Ξ^- is -2. To balance the equation, the sum of the strangeness of the product particles must equal -1. The strangeness of y^+, if it is indeed π^+, would be 0. The unknown particle x^0 must have strangeness of $+1$ to balance the equation (*S* of Ξ^-, which is -2, plus *S* of x^0). The only meson of zero charge with a strangeness of $+1$ is the K^0. K^0 decays into a π^- and a π^+, the particles responsible for trails *h* and *i*, *h* being π^+ and *i* being π^-. The reader may wish to test these tentative identifications by writing the conservation equations, as in the previous example.

"For those who would like to try their hand at this fascinating form of detective work, the accompanying unidentified photograph and drawing [*page 142*] provide an introductory exercise. The interacting particles of this example will be identified in 'The Amateur Scientist' next month."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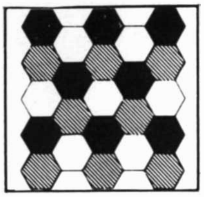

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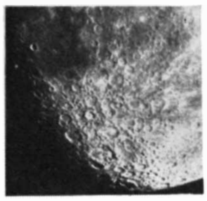

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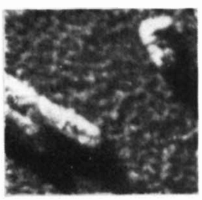

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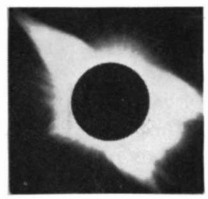

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4S

BOOKS

The brain as a map of the environment

by Frank A. Beach

A Model of the Brain, by J. Z. Young. Oxford at the Clarendon Press ($8).

If Aristotle had described a model of the brain, it would have resembled a refrigerating device used by Plato to chill his wine; Aristotle contended that the highest centers in the nervous system served to cool the blood. The model of the nervous system favored 2,000 years later by René Descartes involved a complicated hydrostatic system of hollow nerve tubes conducting animal spirits to and from the brain; there pores (like the valves in the circulatory system discovered somewhat earlier by William Harvey) opened and closed to direct the fluids to the muscles, which were then caused to produce movement. Sir Charles Sherrington's classic analysis of spinal reflex mechanisms involved the use of models borrowed from the contemporary physics of electricity, and F. R. Lillie's model to illustrate the membrane theory of nerve conduction was an iron wire bathed in acid and coated with a salt.

Thus have men sought to explain the functioning of their own brains by proposing analogies with physical systems or principles, frequently choosing as models human inventions through which those principles were put to practical use. The most recent candidate was born when the simple adding machine of the 19th century spawned today's electric computer, which is said to "learn," "remember" and "make decisions." Designed by human brains to carry out some of the functions of the human brain, the computer has now become a stylish model to explain the operations of the human brain. The results have been exciting and entertaining, and perhaps they will advance our understanding of how the nervous system works.

J. Z. Young's version of "the computer in the skull" is as impressive as it is ingenious. Many of the details of his particular model are dictated by the demands placed on it by a broader concept of the living organism as a self-regulating homeostat. Claude Bernard described the constant "internal environment" that surrounds the organs of the body and supports their essential functions, and Walter B. Cannon used the term "homeostasis" to refer to the maintenance of a steady state within the organism. In keeping with more recent developments, Young expands Cannon's concept to embrace complex organismic behavior: the processes involved in finding, capturing and ingesting food are categorized as homeostatic because they contribute to the maintenance of the organism as a living entity. Inasmuch as the organism's total repertory of self-maintaining activities must be coordinated and directed, there is need in the system for some kind of superordinate governing device. This function is assigned to the brain, which Young describes as an exploratory, self-instructing computer that acts as a controller of the homeostat represented by the organism.

Now, to define an organism in this manner is to imply that all adaptive behavior is homeostatic. Whereas Cannon could limit himself to reflex physiological mechanisms governing vegetative functions such as maintenance of constant body temperature, blood sugar level and so on, Young is placed in the more difficult position of having to deal with much more complicated behavioral functions, including perception, learning, memory and motivation.

Young's outstanding achievements as an investigator of behavioral mechanisms in the brain have included a long list of studies on a variety of species, notably cephalopods such as *Octopus vulgaris* [see "Learning in the Octopus," by Brian B. Boycott; Scientific American, March]. The octopus is an extremely illuminating object for study because its behavior is sufficiently advanced to allow fairly complex learning, because its sensory capacities (including vision and touch) are highly developed and because at the same time its brain is less elaborate and more accessible to experimental manipulation than that of vertebrates with comparable "psychological" status.

The type of analysis employed by Young could begin with a general inquiry into the various kinds of behavior that an animal of a given species must perform if it is to survive and could then proceed to a search for explanations of how the brain mediates such behavior. Homeostasis obviously involves different kinds of adjustment to different kinds of environment, and within the same environment the needs of each species differ from those of its neighbors. Therefore the brain, as the controller of the organismic homeostat, must respond both to the requirements of the species and to the offerings of the environment. This type of reasoning leads Young directly to the consideration of brain mechanisms for sensing and interpreting biologically significant forms of stimulation from the environment.

A key concept in the treatment of sensory stimuli and their functions is that the brains of animals embody models of the external world. In every species the sensory receptors and their central connections possess structural and functional attributes that render the individual animal capable of detecting and responding to precisely those aspects of its environment that are of importance to its effective functioning. Energy changes in the environment are reacted to selectively by the receptor machinery, which processes or "encodes" the resulting "information" for transmission to the brain. A code is "any set of physical events that causes a system to perform some organized task." One straightforward example is represented by the mechanisms of color vision: "Our code of symbols for wavelength differences is limited by the provision of quite a small set of receptors, tuned to wavelengths that occur frequently as features of the environment that are important for our lives. Then, appropriate means of combining these categories are provided by the retinal nervous layers and the brain."

The auditory receptors are likewise "tuned" to particular frequencies that have adaptive significance for the given species. For a bat the ability to sense sounds at 50,000 cycles per second contributes to the detection of small obstacles in its flight path. Primates, including man, have no need to hear sounds at these extremes and are most sensitive to rates of vibration in the region of a few thousand cycles. In general, then, the sensory apparatus of any species encodes and passes on to the brain only that information with adaptive significance for the species. The coding is not, however, completed at the periphery, and a simple filtering process cannot by itself account for adaptive behavior. We are led to examine the more involved problems of perception and Young's notion that the brain contains a map of the environment.

When a fly crawls into the visual field of a hungry frog, the frog slowly turns its head to maintain fixation on the fly and then abruptly leaps in such a direction and for such a distance that a quick flick of its tongue captures the fly. This comparatively simple but highly adaptive response necessitates perception of the nature of the stimulus and its location in space and the translation of this information into appropriate action. Thanks to the construction of the frog's optic system, the spatial location of the fly is precisely correlated with the location of the fly's image on the frog's retina and consequently with the retinal cells that will discharge nerve impulses toward the brain. Each segment of the retina is in turn connected with a circumscribed region in the optic centers of the brain; in effect a map of the visual world is projected on the critical mechanisms of the central nervous system. If different optic regions of the frog's brain are now connected with different subdivisions of the executive or motor areas that control movement, the force and direction of the frog's leap at the fly will be appropriately adjusted to result in the capture of the fly.

By the same token sensory stimuli impinging on the skin can be located because sensory cells at different points on the surface connect with different subareas in the brain structures to which their fibers lead. Sounds of different pitch are discriminated because different cells on the basilar membrane of the inner ear are "tuned" to different frequencies and are connected with different portions of the auditory area of the brain. Thus is the external world projected on or re-presented in the controller of the homeostat.

The anatomical or topographical construction of the central nervous system plays a major role in Young's model. In the grossest sense it is significant that the brains of all higher animals are composed of distinct lobes, each possessing its own input and output and each containing its own kinds of nerve cells with special forms and physiological properties. Equally important are the intralobe subdivisions characterized by further specialization of cell morphology and physiology. In the optic lobe of the octopus, for example, the "fields" formed by the dendritic fibers of a given nerve cell tend to be oriented in either the horizontal or the vertical plane. The significance of such an arrangement is revealed by behavioral tests designed to measure the visual capacities of the animal. An octopus can readily learn to distinguish linear stimuli that are oriented in either the vertical or the horizontal position, but it experiences great difficulty in reacting selectively to the same patterns presented in an oblique position.

In Young's model of the brain the form and the activity of the dendritic trees in the optic lobe are held to constitute fundamental features of the coding system. David H. Hubel and Torsten N. Wiesel of the Harvard Medical School demonstrated that single nerve cells in the cat's visual cortex are selectively responsive to strips of light projected in different positions on the retina. Some nerve cells discharge when the strip is horizontal and others fire only when it is rotated into a different position. Apparently the same principle of organization within the visual system is involved in both mammals and cephalopods. In the case of the octopus each cell in the optic lobe may function as a detector for length, in either the vertical or the horizontal dimension, and aggregations of the two types of cells can act in concert so that a given field of many cells discharges only when a patterned stimulus of the "right" contour and length falls on the retina.

To account for the existence of this isomorphic relation between certain brain mechanisms and crucial features of the environment, Young relies principally on appeals to the forces of mutation and selection in the evolutionary past, and on experimental findings revealing that during the embryonic stages of life connections are laid down in patterns controlled by chemical affinities and mechanical factors. He also points to a supplementary explanation reminiscent of theories proposed by D. O. Hebb of McGill University. The germinal idea is embodied in Young's speculation that "the nervous system might have properties that allow it to be moulded so that . . . it resembles those features of the input that are to be recognized." Hebb proposed in 1948 that recognition of significant stimulus patterns depends on mediation by "cell assemblies" in the brain that have been built up as a result of experience.

The possibility that the mechanisms of perception are at least partly organized by earlier stimulation raises that most imperative question: What is the physical basis of learning? How do life experiences affect the brain and how are such effects preserved? These compelling questions have occupied the attention of Young for three decades or more. A description of his approach can be introduced by recounting the results of a simple experiment.

A hungry octopus is repeatedly presented with a crab, and at the same time the animal is shown a white card bearing either a vertical or a horizontal black rectangle. If the horizontal stimulus is always paired with a punishing electric shock and the vertical one is never accompanied by a shock, the octopus will learn to take the crab when it is associated with the vertical rectangle and to refrain from taking it when it is associated with the horizontal one.

For Young this paradigm represents all learning. Fundamentally learning consists in a choice between two alternatives, in this case to attack or not to attack. Learning is a form of adaptation involving selection among a previously available set of possible alternatives and consisting of reduction of an initial redundancy. This concept is similar to one espoused in 1899 by E. L. Thorndike, who concluded that cats learn to escape from a puzzle box by gradually eliminating all unsuccessful responses and fixating on what is left, namely the successful response. More recently Harry F. Harlow of the University of Wisconsin has championed a comparable explanation of all learning.

Like all other students of the subject, Young is convinced that learning depends on changes within the nervous system, and he has conducted many studies to determine the nature and location of such changes. To deal with the phenomena of perception, learning and memory he relies on a conceptual scheme based on four types of nerve cells. Sensory messages are sorted out in the brain by "classification cells." In the case of a visual stimulus these cells might be those mentioned as having dendritic trees oriented in either the horizontal or the vertical plane. Next are "command cells"; these are the large motor nerve cells with direct connections with effectors. The third category is "memory cells," each of which possesses two and only two outlets to command cells. The fourth is "multipolar cells," which mediate inhibitory processes.

Information arriving at the classification cells is processed and then transmitted to memory cells. In the simplest instance a memory cell can in an octopus directly stimulate a command cell and give rise to an approach response. If, however, the stimulus for the response has previously been associated with painful consequences, the memory cell acts by way of multipolar cells to inhibit approach and perhaps to produce retreat. Learning consists simply in closing off one of the two alternative outlets of the memory cell and thereby increasing or decreasing the probability that a given stimulus will, on repeated presentation, evoke approach or withdrawal.

In terms of anatomy and nerve physiology the most efficient mechanism for immediate response consists of large cells with direct interconnections. Delaying the response and bridging the time interval between one action and the receipt of information about the results of that action call for numerous small cells that have multiple interconnections with their neighbors and produce only local effects within the system. Such cells are found in great numbers in those regions of the brain known to contribute to facilitation and inhibition; they constitute what Young defines as the "computing regions" of the nervous system:

"The neural memory is probably more like an analogue calculator, made by selecting parts from a code set. Moreover, we cannot assume that the effects of past experiences are stored in the brain in the same individual and particulate manner in which this is done in a computer. In animals operations are performed actually in the memory and by the actions of the code elements themselves. The memory is a characteristic of the network itself and in this sense the memory and the representation it contains are the same thing."

In summary, Young's main points are as follows. First, the brain functions as the controller of the homeostat that represents the individual organism. Second, all such control systems operate by making choices between alternative courses of action. Third, the nervous system and the effectors it activates operate by repeated choices between alternatives but function through the parallel action of numerous channels, which provide many alternative actions affording "delicate shades of choice." This in turn demands sensitive detector mechanisms; these are provided by evolution. Fourth, a "learning homeostat" can vary its actions on the basis of previous outcomes. This calls for elaboration of possible alternative responses to the same stimulus pattern. Of primary importance in such a process are the functions of the "result-classifying receptors," which appear to operate in pairs. The pairs are in turn organized in multiple tiers of cells. Fifth, although certain requirements for any change mediating learning are well established, the exact nature of such changes is as yet unknown.

It would be inappropriate to attempt an "evaluation" of the model of the brain presented in Young's book for the simple reason that any worthwhile model must reach beyond established facts and can only be evaluated in terms of the new experiments it suggests. Two judgments can nonetheless be made. One is that Young's model does no violence to anything that is known about either behavior or nerve physiology. The other is that the model does embody a number of ingenious and stimulating ideas that clamor for experimental verification.

Short Reviews

THE CURRENT INTERPRETATION OF WAVE MECHANICS: A CRITICAL STUDY, by Louis De Broglie. Elsevier Publishing Company ($6). De Broglie made his significant contribution to the wave-particle theory of matter in the 1920's—for which he received a Nobel prize in 1929—and for a time thereafter took a view of the theory quite different from that of Niels Bohr and his "Copenhagen school." Beginning about 1930 he departed from his own interpretation because of the technical difficulties it presented and accepted what is currently the orthodox opinion. During the past 10 years, however, he has returned to his original ideas, renouncing the "usual formalism," which, "though strict in appearance and leading generally to precise conclusions, does not provide a profound and a truly convincing explanation of the physical reality on the submicroscopic scale." His earlier interpretation, which he named "the theory of the double solution," is based on the notion that the so-called psi wave intro-

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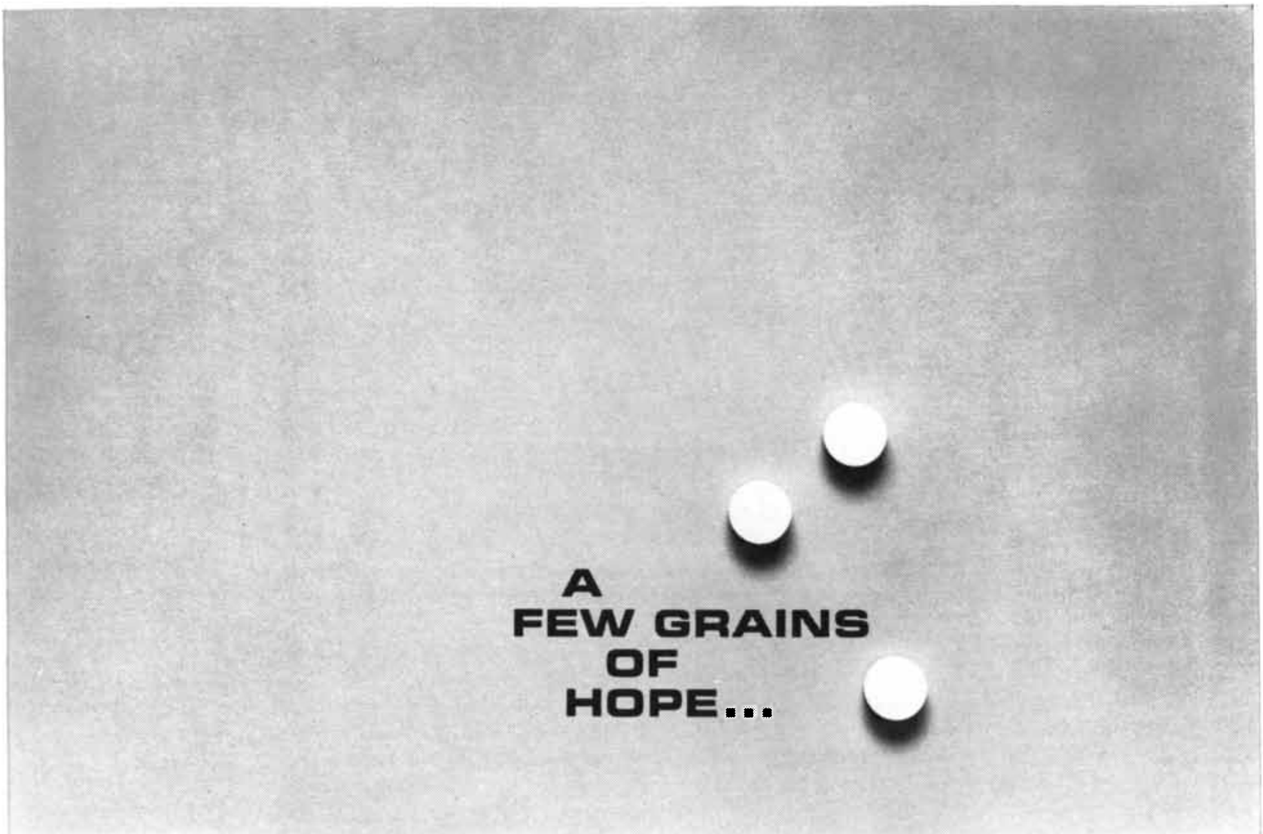

On September 22, 1940, a man with an advanced case of cancer of the prostate was given a new pill. It was a synthetic organic chemical with estrogenic properties of female sex hormones, costing about five cents. Two days later the patient was out of bed. After further doses, he went back to work — hard manual labor — becoming the first proof that a hormone could affect any kind of cancer in man. The age of treatment of cancer by drugs had begun. The man who linked the drug to the disease, Dr. Charles Brenton Huggins, went back to his work — at the University of Chicago — and in 1963 was named one of the winners of the Albert Lasker Awards for Medical Research for his success in the hormone treatment of cancer.* His continuing contributions are part of Chicago's distinguished history of achievement in medical and biological research — work that has its quietly dramatic announcement in books like these:

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THE MANAGEMENT OF WILD MAMMALS IN CAPTIVITY By LEE S. CRANDALL. "The dean of zoo men" shares the experience of 40 years at New York Zoological Park by telling everything about the care of wild mammals, including lively anecdotes. 784 pp. Illus. $13.50

TERATOLOGY JAMES G. WILSON and JOSEF WARKANY, EDITORS. Principles and techniques presented in the 1964 workshop precipitated by effects of thalidomide. 368 pp. Illus. $7.50

GENETICS AND THE SOCIAL BEHAVIOR OF THE DOG By JOHN PAUL SCOTT and JOHN L. FULLER. Far-reaching research on the influence of heredity on behavior as discovered in five breeds of dogs over a thirteen-year period. 448 pp. Illus. $12.50

A MODERN ALGEBRA FOR BIOLOGISTS By HOWARD M. NAHIKIAN. An advanced text book geared to the needs of the biologist and starting with the elements of set theory. 272 pp. $10.00

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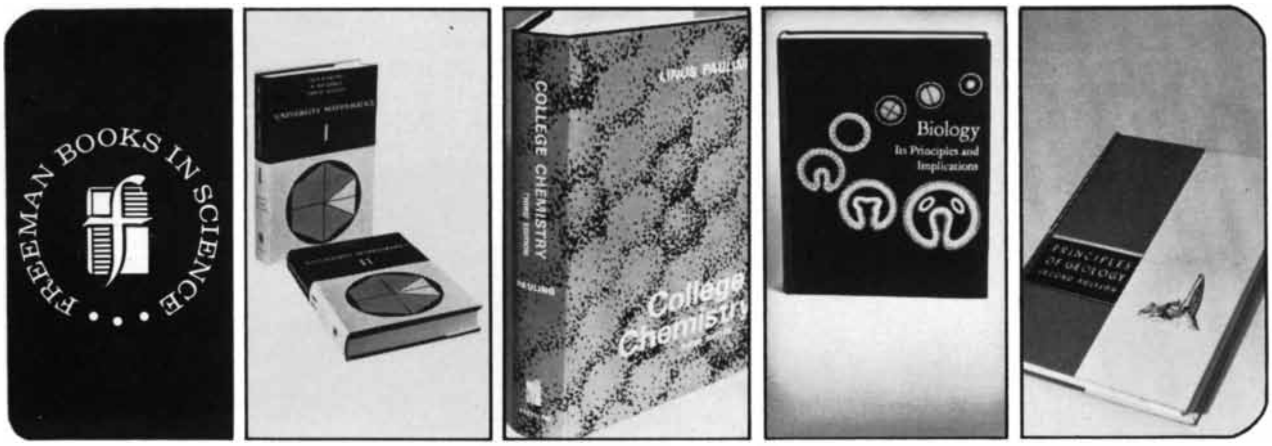

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CHARLES S. THORNTON in *Science*, March 23, 1962

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DEREK A. DAVENPORT in the *Journal of Chemical Education*, November 1964

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duced by Erwin Schrödinger has a hybrid character that leads to serious anomalies and paradoxes, and that if one is to justify the wave-particle duality, one must divide this wave into two parts. One part is "subjective" and helps to localize the particle statistically; the other is "objective" and to be treated like any other electromagnetic phenomenon. No one but an expert is qualified to make of De Broglie's views the same acute critical analysis as he makes of the Copenhagen system, but no one can simply dismiss him with complacency.

John James Audubon, by Alice Ford. The University of Oklahoma Press ($7.95). Audubon's Wildlife, by Edwin Way Teale. The Viking Press ($15). The Audubon Folio, text by George Dock, Jr. Harry N. Abrams, Inc. ($25). A mixed but not unworthy tribute to the greatest nature artist of the U.S. Miss Ford's scholarly biography gives the most complete factual account of Audubon's life that has yet appeared. She is not an exciting writer, but Audubon's life provides excitement enough. Teale's book contains good selections from Audubon's writings; there its merits end. The reproductions of his paintings of birds and animals are shamefully cropped and shoddily presented. The *pièce de résistance* is the Abrams collection of 30 superb reproductions of paintings in Audubon's magnificent folio, accompanied by an excellent essay by George Dock, Jr. The reproductions are stunning; many deserve to be mounted separately so that they can be looked upon and enjoyed again and again instead of merely reposing in a folder on a shelf.

The Deep and the Past, by David B. Ericson and Goesta Wollin. Alfred A. Knopf, Inc. ($6.95). A detailed account of the result of 17 years of investigation in the depths of the oceans, the major purpose of which was to date the recent ice ages and to establish the duration of the Pleistocene epoch, during which man has emerged. The principal technique in this kind of work is to collect "cores"—long cylindrical samples—from the ocean floors. Various methods, among them isotopic dating and the analysis of the tiny shells of foraminifera, are then used to read the story the cores tell of climatic change. The authors' main conclusion, which differs from that of other specialists, is that the Pleistocene began about 1.5 million years ago, at which point the earth became much colder than it had been during the preceding epoch, and that the last intense ice age ended about 11,000 years ago. Stretches of this book are absorbing as examples of scientific resourcefulness, patience and ingenuity; other parts are tedious because of a surfeit of minutiae that are of course essential for the working investigator but tend to overwhelm the general reader. The book can nonetheless be recommended to the nonspecialist as a firsthand description of an important theme of oceanographic research.

Interpersonal Psychoanalysis: The Selected Papers of Clara M. Thompson, edited by Maurice R. Green. Basic Books, Inc., Publishers ($8.50). This edited collection of the late Clara Thompson's papers touches on a variety of subjects, among them changing concepts of modern psychoanalysis, the work of Sándor Ferenczi, Harry Stack Sullivan and Erich Fromm, the psychology of women and the problems of womanhood—all fields in which she was particularly interested. Dr. Thompson was not an innovator and made no significant contributions to theory, but she was a first-rate practicing therapist and an excellent administrator of psychoanalytic organizations. Her writings convey the impression of a singularly clear-minded, independent and courageous woman.

Atoms, Molecules and Quanta, by Arthur Edward Ruark and Harold Clayton Urey. Dover Publications, Inc. ($5). This book, first published in 1930, had a long, influential career as an educational tool. It presents the older views of the physics of atoms and molecules, and their interaction with radiation and bombarding particles, that laid the foundations for quantum mechanics, and explains the laws and basic ideas of the revolutionary new method. Because the fundamentals of the subject were well understood before the book was written, it has not outlived its usefulness. In preparing a second edition the authors have accordingly confined revisions to the correction of errors, the updating of fundamental constants, the enlargement of the bibliographical data and the addition of a number of supplementary notes. A two-volume paperback.

Mammals of the World, by Ernest P. Walker and associates. The Johns Hopkins Press ($37.50). These three volumes, a monumental labor of more than 30 years, are a major contribution to the literature of zoology. They constitute a basic reference work covering all the known and present genera of mammalian life on earth. Each genus (and often several different species of the genus) is fully described, and information is provided as to habits, habitat, diet, mating and so on. There is at least one photograph of every animal mentioned. Many of these were extremely hard to obtain; some are quite unsatisfactory or even, as in the case of *Homo sapiens,* absurd. This stricture is negligible, however, when matched against the achievements of a splendid work of natural history.

SEXUAL DEVIATION, by Anthony Storr. Penguin Books (85 cents). This paperback original by a British physician and psychoanalyst is one of the soundest introductions of its kind. It deals with all forms of sexual deviation, from sadomasochism and homosexuality to voyeurism, buggery and paedophilia, discusses theories as to the origins and causes of these disorders (sexual guilt, sexual inferiority and so on) and considers the nature and effectiveness of contemporary forms of therapy. The book stands out for its freedom from prejudice and its sympathy. It makes clear to what extent every human being is all in all, that is, how numerous are the strands of sexual deviation even in the "normal," well-adjusted person who achieves fulfillment in his sexual life.

ALEXANDER VON HUMBOLDT, by L. Kellner. Oxford University Press ($5.75). Friedrich Wilhelm Karl Heinrich Alexander, Baron von Humboldt, was a man with as many capacities and interests as he had names. He was a scientific explorer who spent years in South America surveying and botanizing; as chamberlain to Prussia's Friedrich Wilhelm III he was a pioneer in organizing international scientific conferences; he contributed to physical geography, meteorology and geology. When he was 75 years old (in 1845), he published the first of five volumes of his renowned work on the physical world—*Kosmos*—and he continued his vigorous activities until his 90th year. Dr. Kellner's book is a modest-sized, dependable and congenial account of this exceptional man's life.

THE TYPOGRAPHIC BOOK 1450–1935, by Stanley Morison and Kenneth Day. The University of Chicago Press ($30). A revised version of Morison's noted folio *Four Centuries of Fine Printing,* this strikingly handsome volume presents more than 350 title and text pages drawn from presses working in the European tradition through five centuries. Included is an introductory essay by Morison and supplementary material by Kenneth Day covering the period 1925 to 1935.

THE MECHANISTIC CONCEPTION OF LIFE, by Jacques Loeb. The Belknap Press of Harvard University Press ($4.25). A reissue, edited by Donald Fleming (who also adds an informative introduction), of a collection of essays by the well-known German-American experimental biologist remembered for his classic researches on heliotropism and artificial parthenogenesis and for his evangelism on behalf of a mechanistic philosophy that treated life as a purely physicochemical phenomenon. Within this framework Loeb found a place for a rational human ethic that would purge society of its follies and bring about a life of reason.

DEPRESSION, edited by E. Beresford Davies. Cambridge University Press ($17.50). The proceedings of this 1959 symposium held in Britain by the Cambridge Postgraduate Medical School include a number of review papers on contemporary knowledge of depression, discussions of its psychological and psychopathological aspects, of its treatment with drugs and other methods. The net impression is that the progress made up to this time in fighting this serious and widespread disease is, in a word, depressing.

ACCIDENT RESEARCH, edited by William Haddon, Jr., Edward A. Suchman and David Klein. Harper & Row, Publishers ($15). The editors bring together a large number of case studies of all types of accidents—children bumping their heads on metal toys, suburban householders slicing themselves up with power lawn mowers, automobile accidents caused by drunken drivers, airplane crashes due to pilot error—and attempt to evaluate progress in the systematic investigation of causes and prevention that has used the techniques of psychology, sociology, engineering and operations research.

SUCCESSIVE APPROXIMATION, by N. Ya. Vilenkin. The Macmillan Company ($2.25). Mathematics being the handmaiden as well as the queen of the sciences, one of its most important duties is to furnish the approximate solutions of problems that will meet the needs of engineers and experimental scientists in almost every field. This little book in the series "Popular Lectures in Mathematics"—the word "popular" is itself a crude approximation—introduces the subject to high school and college students.

THE GEOGRAPHY OF MODERN AFRICA, by William A. Hance. Columbia University Press ($12). A comprehensive economic geography of Africa—well illustrated, clearly written, packed with statistical, demographic, political and economic information. Some of these facts are amazing and serve as an antidote to popular misconceptions about a great continent that is almost as surprising to us as it was to the Romans.

THIS IS PSYCHIATRY, by Felix von Mendelssohn. Franklin Watts, Inc. ($7.95). This rather muddling, superficial and not very informative book attempts "to provide guidance through the easily confusing maze that constitutes modern psychiatry." It hints at deep thoughts, leaving them half-explained, and it is laden with jargon. The volume is cheaply made and clad, has no illustrations or diagrams, contains only 237 pages, costs as much as transportation from Washington to New York and carries the reader nowhere.

Notes

THE GROWTH OF WORLD INDUSTRY, 1938–1961. United Nations ($10). This volume consists of tables that show the growth in industrial output and employment and the changes that took place in the mining, manufacturing, construction, electricity and gas industries in roughly 100 countries or territories of the world from Algeria to Yugoslavia during the years 1938 to 1961. The text is in both French and English.

VENTURES IN CRIMINOLOGY, by Sheldon and Eleanor Glueck. Harvard University Press ($11). Selected papers of two leading students of criminology, the focus of interest being the causes, prevention and treatment of juvenile delinquency. Included is an extensive bibliography of the writings of the Gluecks since 1923.

CIRCULATION OF THE BLOOD: MEN AND IDEAS, edited by Alfred P. Fishman and Dickinson W. Richards. Oxford University Press ($18). This richly illustrated book consists of 12 chapters by various specialists, dealing with the history of cardiovascular physiology.

THE FLIGHT OF THUNDERBOLTS, by Sir Basil Schonland. Oxford University

Press ($4.80). A second, revised and enlarged edition of an authoritative and readable book on the nature, causes and effects of lightning, the first edition of which was reviewed at length in these pages in June, 1951.

COLLECTED PAPERS OF P. L. KAPITZA, edited by D. ter Haar. The Macmillan Company ($20). This volume is the first of three that are to present the scientific papers and some of the semipopular essays of a noted physicist. The set is intended as a tribute to Kapitza on his 70th birthday.

THE FRENCH REVOLUTION FROM 1793–1799, by Georges Lefebvre. Columbia University Press ($7.50). A translation into English of the second half of Lefebvre's outstanding history. The first volume was published in 1962.

PALEOMAGNETISM, by E. Irving. John Wiley & Sons, Inc. ($19.50). A monograph on the many important geological and geophysical problems that are dealt with by paleomagnetism.

WATER RESOURCES, USE AND MANAGEMENT. Cambridge University Press ($35). Proceedings of a 1963 symposium held in Canberra by the Australian Academy of Science, presenting some 40 papers and discussions dealing with topics from meteorology to the socioeconomic side of water development.

BIOGRAPHICAL MEMOIRS OF FELLOWS OF THE ROYAL SOCIETY, VOLUME IX. The Royal Society ($6). This collection includes memoirs of Niels Bohr, C. G. Darwin, John Read, R. A. Fisher and G. M. Trevelyan. Portraits and bibliographies.

THE BEGINNINGS OF MODERN SCIENCE, edited by René Taton. Basic Books, Inc. ($17.50). This second volume of the Taton history translated from the French covers the period from 1450 to 1800. Plates and illustrations.

THE PROTEINS: COMPOSITION, STRUCTURE AND FUNCTION, VOLUME II, edited by Hans Neurath. Academic Press ($26). The second edition of this treatise deals with the fundamental properties of proteins in solution and in the solid state.

PROGRESS IN SOLID-STATE CHEMISTRY, edited by Howard Reiss. The Macmillan Company ($17.50). The beginning of a new series of critical reviews in this subject, including surveys of research progress.

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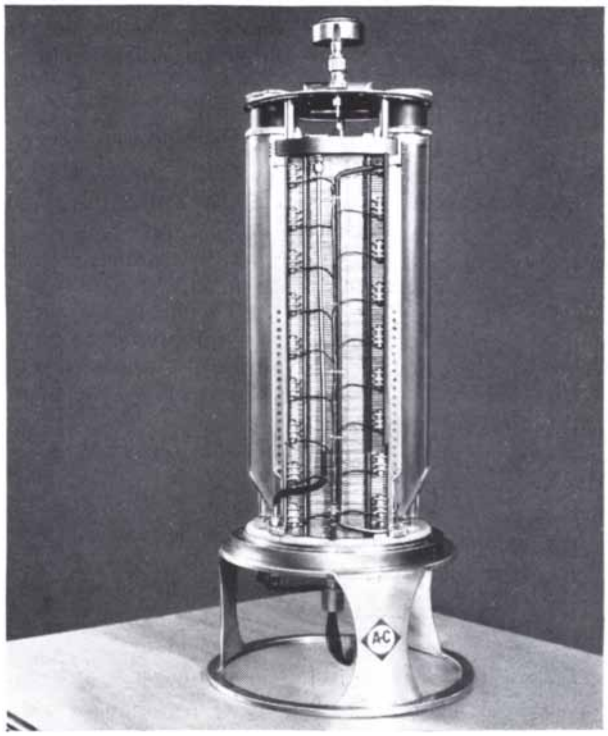

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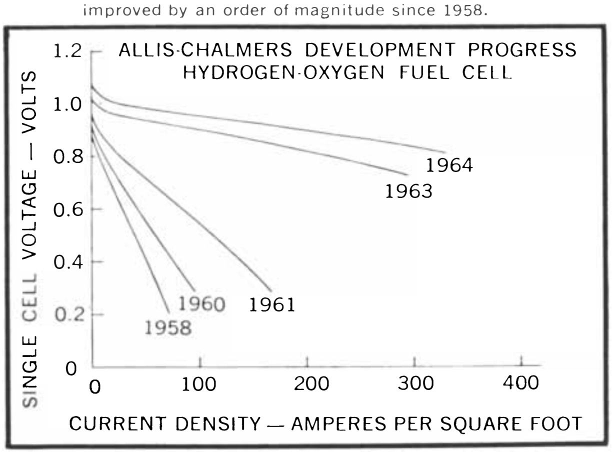

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