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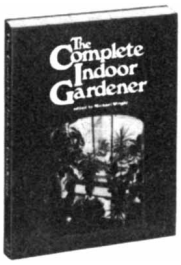


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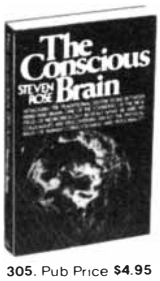


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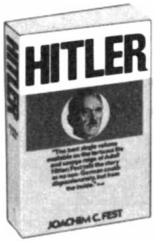


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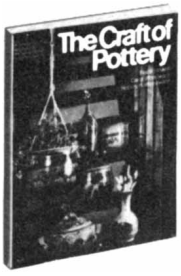


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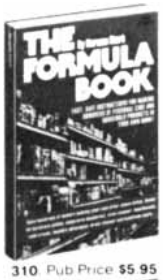


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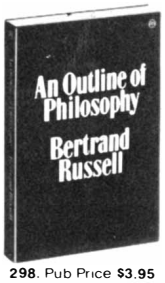


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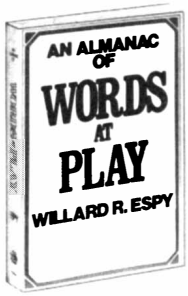


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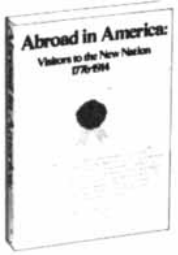


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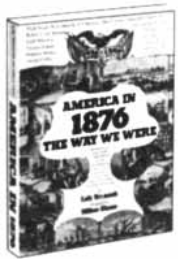


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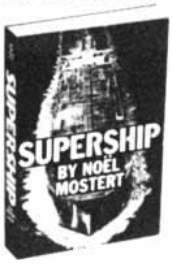


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# One reason you may be looking for new speakers could be the phase distortion present in those you listen to now.

**Phase Distortion Explained.** Phase distortion is heard as a blurred sound picture and prevents accurate localization of instruments. It is most noticeable in the lower mid-frequency range at higher volumes. It occurs in most conventional, multi-way loudspeakers at the crossover point, when the same note is being reproduced by two drivers. Because today's high quality loudspeakers have virtually solved the problems of frequency response as well as harmonic and intermodulation distortion, the study and correction of phase distortion is all the more important if you are to literally recreate the original performance.

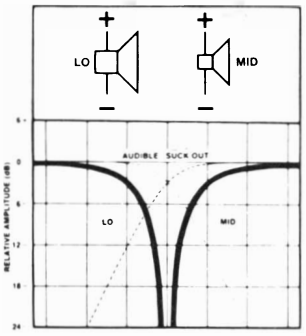



Diagram A. When drivers are placed in-phase, a problem of audible "suck out" is created.

**Our Research.** At the 1973 AES convention in Rotterdam, two Bang & Oulfsen engineers, Madsen and Hansen, presented a paper on audible phase distortion. This paper represented three years of concentrated research within which they developed an electronic crossover, tri-amplified loudspeaker that allowed them to demonstrate three important facts: 1. Phase distortion did indeed exist in loudspeakers. 2. That it was audible. (Hundreds of hours of critical listening tests confirmed this.) 3. That it could be effectively eliminated through sophisticated technology.

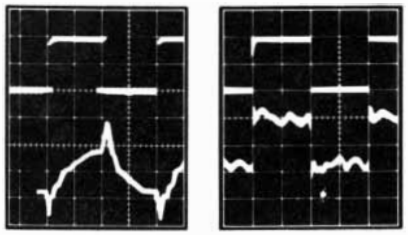


Diagram B. A high quality conventional loudspeaker (left) and our new Phase-Link loudspeaker (right) reproducing a square wave. What happens to the square wave is what happens to music.

**Our Product.** The experimental speaker developed by Madsen and Hansen was far too expensive to consider for distribution to the audio consumer. A practical solution had to be found.

At this point, Bang & Olufsen engineer E. Baekgaard began his work with mathematical computer simulation. He discovered that the fixed phase shift, present in most conventional speakers (drivers alternated 180° out-of-phase) could be "cured" by placing all drivers in-phase. However, when this was done, an audible amplitude "suck out" was created (See diagram A.). It was to solve this problem that an additional narrow band filler driver – the Phase-Link™ Driver – was developed. Its compensating signal cured the amplitude "suck out" and the variable phase shift. It made the audible output of the loudspeaker virtually identical to the input – the square wave, for example.

**Another Refinement.** Phase-Link™ loudspeakers have their drivers mounted on a common acoustic axis so that the sound from each driver will reach your ears simultaneously. That is the reason for our slightly canted grill.

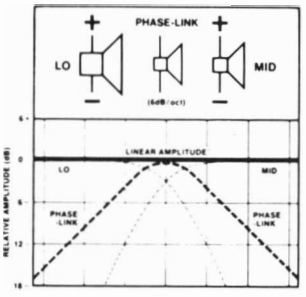
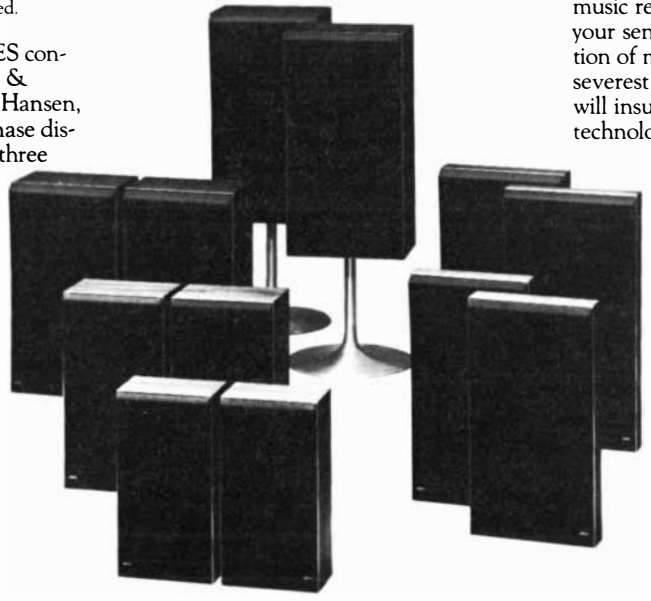



Diagram C. Our new Phase-Link filler driver provides a compensating signal to eliminate "suck out" and variable phase shift.

**Your Listening Experience.** The importance of our new Phase-Link™ technology and square wave tests is of course determined by the fidelity of the music recreated by our speakers. It is your sensitivity to the accurate reproduction of music that will give them their severest test. It is our technology which will insure they pass, for rarely has technology served music so well.



Because the ear is sensitive to phase distortion mainly in the lower mid-frequencies, Phase-Link is used between the low-frequency driver and the mid-range unit in the high power, 3-way systems (M-70, S-60) but not between the mid-range and tweeter. In medium-power, 2-way systems, one Phase-Link driver is used in 12dB/oct. filter combinations (S-45, P-45). Low-power, 2-way systems (S-30, P-30) do not utilize a Phase-Link driver but instead eliminate phase distortion through a sophisticated 6dB/oct. filter technique.

Bang & Olufsen speakers include the M-70, shown on trumpet stand (supplied), three bookshelf models, the S-60, S-45, and S-30, and two wall panel speakers, the P-45 and P-30.

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Established 1845 **SCIENTIFIC AMERICAN** July 1976 Volume 235 Number 1

ARTICLES



DEPARTMENTS





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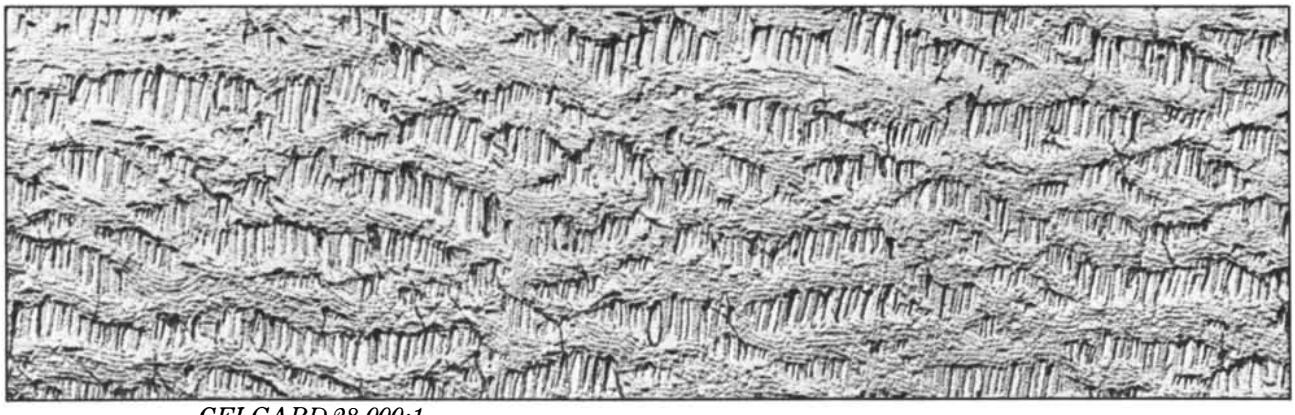

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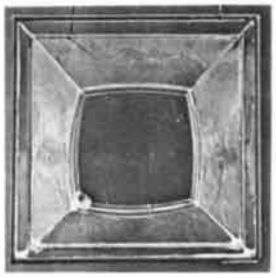

## THE COVER

The photograph on the cover shows a roughly cubic soap bubble embedded in a configuration of soap films spanning a wire-frame cube some three inches on a side. The films are formed by first dipping the wire frame in a solution of soapy water; when the frame is lifted from the soapy water, 12 nearly flat surfaces appear, originating at the 12 edges of the cube. Although the 12 surfaces are directed generally toward the center of the cube, they never meet there; instead a small, almost square plane develops in one direction or another in the middle of the cube. If one then blows a soap bubble gently in contact with the central plane, the bubble assumes the rounded cubic form seen in the cover photograph. (An oblique view of the same shape appears on page 93.) The basic mathematical principles governing such forms are explained in the article "The Geometry of Soap Films and Soap Bubbles," which begins on page 82.

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Cover photograph by Fritz Goro

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# LETTERS

Sirs:

I found the article by Dorothy Nelkin ["The Science-Textbook Controversies," SCIENTIFIC AMERICAN, April] helpful, disturbing and incomplete. It was helpful in describing the feelings of one involved in the scientific enterprise reacting to attacks on that field of endeavor. It was disturbing because it reflected a bias on the author's part that went beyond scientific objectivity. And it was incomplete because it seemed that she had not read much from "scientific creationists" that supported their position.

The scientific community has succeeded in many endeavors. But it does not admit its nonrational bases, its limitations, its struggles to find truth, the distinction between hard data and the popularization of that material, and the effect of science on human values.

The bases of science are nonrational and related more to philosophy and theology than to rational thought. Let me give some questions that may illustrate this statement. Why is there something and not nothing? Can we have science without honesty, logic, memory and generalization, which rest more on faith judgments proved to be valid by testing than on prior rational proof? Why, indeed, should a man or a woman be a scientist?

Science is limited to natural explanations of natural phenomena. You cannot put God in a test tube or measure Him with instruments because he is Spirit. Yet the effect He has had on people is immeasurable. To say that science is limited to natural explanations of natural phenomena is an objective statement. To say that science gives explanations for all phenomena is a subjective judgment open to differences of opinion.

In the area of the struggles of scientists the author does a good job of describing what really goes on with what is projected to the public. Rarely is there a direct line from hypothesis to positive proof. Answers come more often by the hard work of trial-and-error testing, suggestions by others, intuition and chance.

Lastly, the scientific community needs to come to grips with its effects on public life, morals and values. The results of science and technology have been good and bad. Better food, medicine, means of travel and communication and so on have enriched our lives. But pollution of various kinds, the prostitution of science and technology and the increasing intrusion of science and government into the arena of human values pose a threat. We are coming into an era of experimentation on human beings that asks only "Is it possible?" and "Is it feasible?" and leaves out the question "Is it right?"

To some, science is a sacred cow. It has sacred writings, high priests, religious practitioners and popularizers. But it is not God. While this field of human endeavor is less affected by bias, corruption and politics than many others, it is still not 100 percent clean and pure. It is long overdue for self-criticism and correction. If the scientific community does not do it itself, then others are willing to step in and take on that role.

WILLIAM H. KOENIG

Pastor
First Baptist Church
Fort Bragg, Calif.

Sirs:

. . . Most fundamental of author Nelkin's assumptions is one having to do with the relationship of science to theories or models of origins and prehistory. Creationists do *not* advance special creation as a scientific theory, because it is not possible to test experimentally and potentially falsify the creationist model of origins. By the same token evolutionary explanations of origins also fall outside the realm of science strictly defined, because they too are unfalsifiable. And creationists have very respectable support in this position, for example from science logician Karl Popper, biologists such as Paul Ehrlich, L. C. Birch and P. B. Medawar, computer specialist Murray Eden and paleontologist Everett C. Olson.

If evolutionary theory, then, is unfalsifiable, it is not actually a theory of science. It follows that "fundamentalist textbook critics," to use author Nelkin's words, are not as she assumes participating in a "growing criticism of scientific rationality." They are, on the contrary, making a very rational distinction between science and philosophy or


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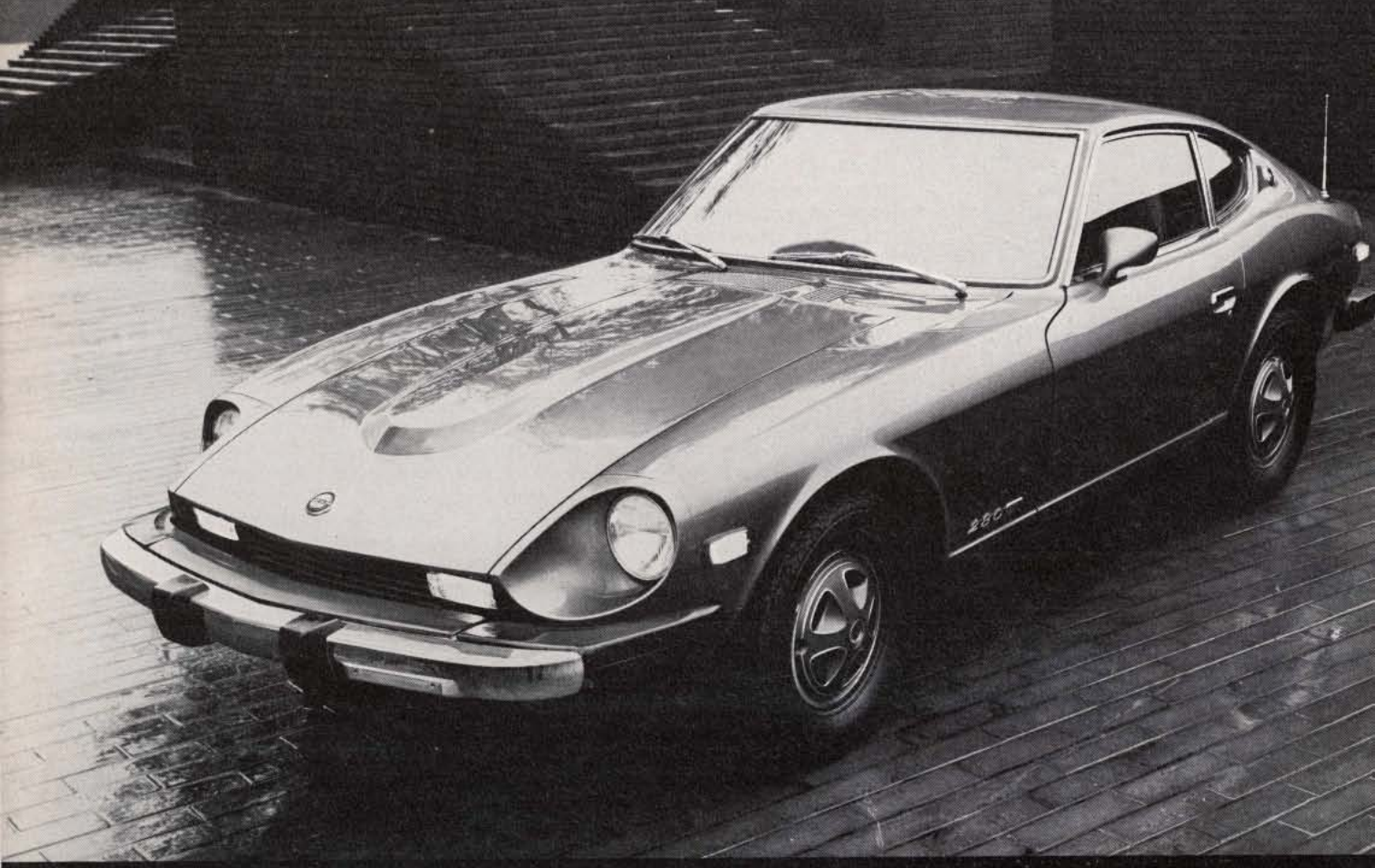

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metaphysics, in accord with Popper's "criterion of demarcation"—falsifiability....

Author Nelkin apparently assumes that professionals and "experts" create the best textbooks and curricula and that effective review by nonprofessionals and nonexperts would degrade the excellence of education. This proposition is destroyed by brief reflection on the almost cosmic catastrophe created by the professionals and experts when they replaced the teaching of reading by phonics with the "look-see" method and displaced traditional math with the so-called "modern math." The result has been a generation of high school graduates who can neither read nor write effectively nor perform long division, but who are oh-so-knowledgeable about birth-control techniques and the (evolution-based) arguments for abortion on demand (Federally funded, of course). Need it be pointed out that many thousands of "ignorant" nonprofessionals saw immediately that the new reading and math programs were terrible blunders? But for years the professionals would not listen. They knew best. And several decades later, when the abysmal test results began to pour in by the multiplied millions, one would think the "experts" could gracefully admit their error and move for a change back to the proved traditional methods—but no, it is like pulling teeth to get them off the backs of lay people who are only supposed to beget children and pay taxes to support the "experts."

The mention of taxes brings to mind the subject of money. For Bible-believing Christians this is one of the most galling factors in the present situation. They see tens of millions of their Federal and state tax dollars going not only to support the very ample salaries of anti-Christian curriculum experts and social scientists but also to finance printing, promotional advertising and teacher-training courses in state schools. And the National Science Foundation fights ferociously to keep every penny of the funds it wants to use for these purposes. Moreover, as if to add insult to injury, when Congress knocks out the funds for MACOS, President Ford hurries to put them back in the budget....


ROBERT E. KOFAHL, PH. D.

Science Coordinator
Creation-Science Research Center
San Diego, Calif.


Sirs:

I thought your readers might be interested in knowing something of the results of an unpublished survey of Illinois high school biology teachers that was conducted by an honors freshman biology class I taught in the fall of 1972. Our respondents represented several hundred teachers from both rural and metropolitan areas within the state. Neither my students nor I were professional sociologists, but we did obtain guidance from members of the staff of the University of Illinois Survey Research Laboratory in picking our sample and drawing up our questionnaire. Thus while I am well aware of our amateur status in this field, I doubt if our results are likely to be unrepresentative or biased to any significant degree.

We found that although 56 percent of our respondents thought that only the Darwinian theory of evolution should be included in textbooks, and none thought that only the creationist view should be presented, 38 percent of the teachers believed both viewpoints should be equally presented. In fact, 38 percent of the teachers reported they *currently* taught both theories. Furthermore, 63 percent of the teachers reported that they would not be opposed to future editions of the textbooks they were currently using presenting both theories on an equal basis.

Although we found that 58 percent of the teachers reported they had never encountered any difficulty with students, parents or the public in teaching Darwin's theory, a significant number (34 percent) reported some difficulty. In 71 percent of the cases this difficulty was largely with students and in another 18 percent with parents.

It seems clear from our survey that the fairness doctrine and equal-time considerations Professor Nelkin so ably discussed have in fact made a deep impression on high school biology teachers in at least one state.


PHILIP L. CARL

Department of Microbiology
University of Illinois
at Urbana-Champaign
Urbana


Sirs:

Professor Nelkin discusses the efforts of antievolutionists to compel the representation of a scientific theory as a hypothesis. Efforts of this kind have a long history. In 1615 Galileo wrote to his friend and pupil Benedetto Castelli, professor of mathematics in Pisa, and suggested that a literal interpretation of the Bible should not be maintained if it is contrary to scientific evidence. When this view became known, Galileo was attacked and denounced in the Holy Office in Rome. The preliminary investigation was conducted by Cardinal Bellarmine, and the case against Galileo was dropped. The purpose of this letter is, to quote a similar suggestion from a letter written at that time by Cardinal Bellarmine to a friend of Galileo's. Bellarmine wrote:

"I think that you and Galileo would act more prudently if you presented your opinions as a hypothesis and not as an absolute truth. To assert that the earth is really moving is a very dangerous thing, because it would irritate the philosophers and theologians. To prove that the hypothesis of the immobility of the sun and the moving earth saves the appearances is not at all the same thing as to demonstrate the reality of the movement of the earth. I believe one can prove the first point, but I doubt strongly whether one can prove the second point,

and in case of doubt one must not abandon the sense of the Holy Bible in which it has been interpreted by the Holy Fathers."

N. L. BALAZS

Max-Planck-Institut für Kernphysik
Heidelberg

Sirs:

My article "The Science-Textbook Controversies" explored the social and political tensions that sustain objections to the teaching of science in public schools. It suggested three themes that pervade the textbook disputes: a concern that science influences traditional moral and religious values, a resentment of the authority represented by science (particularly the authority expressed in the professionalization of education) and a demand that science should be more closely related to egalitarian and pluralist political values. The article used the debates to explore briefly some problems in the public understanding of science.

The article provoked a large number of letters, some friendly and some not so friendly, most of the latter from creationists. It is impossible to respond directly to much of the criticism. Did God create the universe? Is the Bible a source of scientific information? Will rigorous scientific scrutiny validate the concept of evolution? How does science bear on moral values? Is Nelkin hopelessly prejudiced by her "faith" in science?

Since most of my correspondents used the article to express their own thoughts on science, it seems useful to provide a brief summary of the major ideas in the letters. They focused on three general questions:

*What is science?* Science, asserted many writers (both pro-creationist and pro-evolutionist) is "proved truth." It implies an "absolute quality." Some suggested that the function of science is to learn about the order created by God in order to substantiate His existence. Others argued that science is only one of many different paths to "truth" and that scientists (and Nelkin) are "arrogant" and "dogmatic," "blinded" by their unwillingness to accept the Bible as a scientific document.

*What is the concept of evolution?* This question entailed extended and bitter criticism. Creationists argue that evolution is not science because it cannot be falsified and is difficult to verify with demonstrable facts. It is, maintained critics, only a "theory of history," a "philosophy" or a "religion" and therefore must be balanced with an understanding of the Bible. Evolutionary studies are currently based on false premises because they assume that God does not intervene in the working of the universe. Some letters argued that scientists (and Nelkin) are so irrationally committed to certain premises that they are unable to present any facts to refute creation theory. "Religiously" adhering to science (narrowly defined), we ignore well-founded minority views within the scientific community.

*What social problems arise from the teaching of evolution?* To substitute science for religion compounds moral and social problems (abortion and Communism were most often cited). Teaching creation theory is necessary for moral development, and it would also restore the literacy destroyed by professional educators more concerned with science than with religion and totally out of touch with the needs of the American people. Science education must be based on "American values of democracy, freedom of choice, equality and fairness."

Briefly, then, the response to my discussion of the science-textbook debates suggests that to those critical of science the social and moral implications associated with a scientific concept may vastly override any details of scientific evidence. It is important, I feel, for the scientific community to appreciate this point, since it bears on how science can be understood and received. The volume and tone of the mail suggest the wide appeal of the sentiments expressed by critics who have managed to fuse three pieties of American culture: science, religion and populist democracy.

DOROTHY NELKIN

Cornell University
Ithaca, N.Y.

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# 50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

JULY, 1926: "Throughout the later years of Arctic exploration it has been the dream of the explorer to fly to the North Pole, and also to unlock the secrets of that vast area which lies between the Pole and the northern coasts of Alaska and Siberia. The successful accomplishment of both of these hazardous undertakings will make the year 1926 forever memorable in the annals of Arctic exploration. To Lieutenant Commander R. E. Byrd, U.S.N., fell the honor of being the first man to reach the Pole by airplane, which he did in a continuous flight of 1,200 miles in an all-metal multi-engined monoplane, starting from Spitzbergen and returning to the same base. To that veteran explorer Amundsen, assisted by the American, Ellsworth, and the Italian, Nobile, it was given to fly in an Italian-built semi-rigid dirigible from Spitzbergen to the Pole; onward to Point Barrow on the Alaskan coast; and thence to Teller, near Nome, in a continuous flight of 2,700 miles, lasting 71 hours, in the latter part of which he fought his way against fog, ice and blustering winds."

"Scientific developments that will revolutionize the presentation of motion pictures have just been announced as perfected by the Western Electric Company and Warner Bros. Pictures, Inc. They involve a system for the synchronization of motion pictures with reproduced sound having a degree of naturalness never before attained. The system represents the successful combination and conversion to motion-picture use of two major research developments. The first of these is a high-quality microphone of an improved type, electrical amplifying apparatus and a record-cutting mechanism. Recording can be carried on at a considerable distance from the source of the sound, so that the actors can be grouped naturally in any scene and need not be crowded before a microphone. The second feature is a remarkable electrical reproducer, which converts the movements of a needle in the grooves of a sound record into electrical vibrations. The electrical currents from this device pass into an amplifier and then operate a high-quality loudspeaker of an improved type capable of filling any motion-picture auditorium with sound."

"The United States has the unenviable distinction of reporting more smallpox cases during 1925 than any other country except India, namely 43,193 cases, according to reports that have been received by the American Association for Medical Progress from the health officers of all but one state (Utah). Most of the states do not report the vaccinal condition in cases of smallpox. In 17 states and the District of Columbia such reports are available for most of the cases—10,636 out of the total of 12,858 cases in those areas. Among these cases 9,660 cases, or more than nine-tenths, had never been vaccinated, and 751 cases, about 7 per cent, had been vaccinated from seven to 50 years previously. Thirteen states each reported more than 1,000 cases of smallpox in 1925, California leading with 4,921 cases, followed closely by Alabama (4,288) and Ohio (4,018). Indiana had 2,996 cases; Georgia, 2,108; Washington, 2,004; North Carolina, 1,920; Tennessee, 1,805; Kentucky, 1,700; Illinois, 1,625; Wisconsin, 1,517; Texas, 1,309; Mississippi, 1,216. All of the six New England states together had only 102 cases, 94 of which were in Rhode Island."

"Radio engineers are building an invisible talk-bridge to span the distance of 3,000 miles between New York and London, with the ultimate aim of establishing general radiophone service between the Old World and the New. The experiments began in 1922, and they are still in progress with no definite clue as to when the vagaries of the ether will be conquered so that commercial service can be offered to the public. The problem is to reduce the mortality of words in their flight across the water. During the summer of 1923 about 15 words out of 100, on an average, would survive the trip across the Atlantic. Last summer the transmission was improved so that the record was 60 out of 100 words received. On an average, during the past winter, 90 out of 100 words could be identified, and during certain hours the complete word list was easily understood."

"The meteors and the aurora are the only witnesses that give testimony concerning the constitution of the higher regions of the atmosphere. The lower layers of the atmosphere, on the other hand, are subject to direct study, either by direct visual observation or through the intermediary of instruments. So far as the purposes of meteorology are concerned, satisfactory results can be had by sending instruments aloft unattended by an observer. Sounding balloons made of very thin sheet rubber of the best quality and constructed to release the instruments they carry—themselves marvels of lightness—at the highest point of their travel, so that they can settle to the earth in a parachute, have been much used for this purpose. Such a balloon liberated by the German meteorological service reached the surprising height of nearly 22 miles. Dr. Goddard has thought to apply the rocket in this work, and has done a great amount of scientific research in an effort to put the project on a sound physical basis, the results being of a character to give great hope of this device being developed to a point where it will allow of instruments—gas-collecting apparatus and the like—being sent to the

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very highest levels of the atmosphere, and indeed even into the empty region beyond."

"In a paper read before the Physiological Society in England, E. D. Adrian of the University of Cambridge suggests the possibility of eavesdropping on the human brain by means of radio instruments, in which vacuum-tube amplifiers play an important part. Dr. Adrian said he believed that within the next few years it should be possible to read the main types of brain messages passing down from the brain via the nerves to the muscles. The passing of the messages down the nerves seems to cause an electrical disturbance, and Dr. Adrian's apparatus records on a rapidly moving photographic plate the impulses along a single fiber. He 'decodes' the nerve impulse by segregating a single fiber of the system. He points out that the sense organs in the skin that register temperature, touch and pain are too close together for easy segregation but that the fibers in the muscles are farther apart and can be used as a link between the brain and the radio recorder."

SCIENTIFIC AMERICAN

JULY, 1876: "An interesting discussion has recently taken place in the French Academy of Sciences on the question of the influence of solar radiation and of green matter in the formation of the immediate principles of plant organisms. M. Boussingault considers this influence to be indispensable, and that if the solar radiation should disappear, life would be impossible. M. Pasteur, on the other hand, thinks that life might still continue in certain inferior plants and occasion the most complete organic growths. M. Pasteur's determination that oxygen and light are not essentials of life, and his having caused organisms to exist in an atmosphere of carbonic acid and in absolute darkness, are among the greatest triumphs of modern chemistry."

"In her scientific cruise of three years and a half the *Challenger* steamed and sailed 68,930 miles, crossing both the Atlantic and the Pacific, the former several times. The deepest soundings were 4,575 fathoms, in the Pacific between the Admiralty Islands and Japan; and in the Atlantic 3,875 fathoms, 90 miles north of the island of St. Thomas in the West Indies. We have noticed the principal movements of the expedition from time to time. Its return to England has revived public interest in the work of Professor Wyville Thomson and his associates. Many curious animals were brought home. One very odd specimen, which came to the surface only at night, is described as having a body so transparent as to render visible all the nerves, muscles and internal organs."

"An international committee has been formed for the exploration of the Isthmus of

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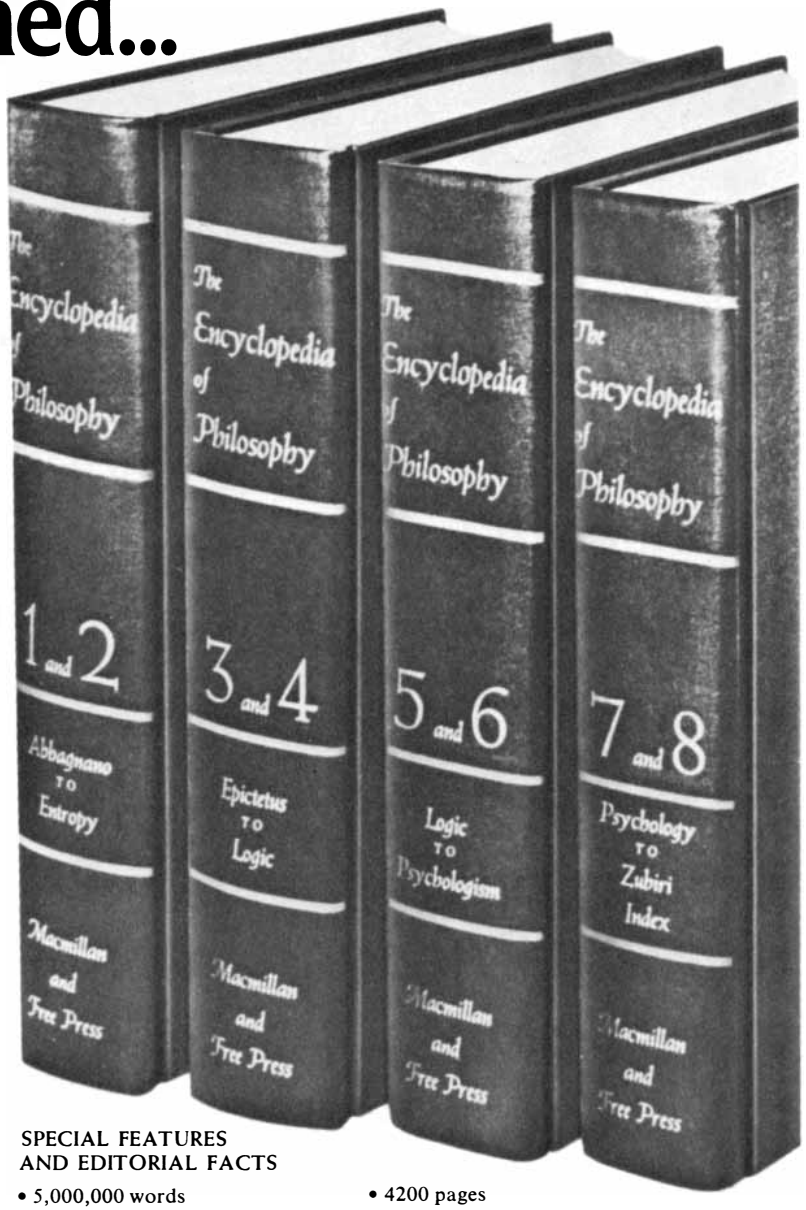


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| Free Will | The Absolute | Existentialism | Humanism | Truth | Linguistics |

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|---|---|---|---|---|
| CONFUCIUS | SANTAYANA | DESCARTES | KANT | RUSSELL |
| ERASMUS | SPINOZA | HEGEL | NIETZSCHE | EINSTEIN |
| SARTRE | THOMAS AQUINAS | CAMUS | ARISTOTLE | NEWTON |
| LOCKE | WITTGENSTEIN | KIERKEGAARD | PLATO | PIAGET |

Darien to determine a route for a canal. Ferdinand de Lesseps (projector and builder of the Suez Canal) reports that the committee of the French Academy on commercial geography has accepted and approved the idea of beginning a topographical, botanical, zoological and ethnological exploration of the Isthmus."

"In an educational exhibit at the Centennial Exposition the Massachusetts Institute of Technology provides complete catalogues of all the articles exhibited, with documents explaining the organization of the school and various other details of interest. The general plan of the institution is quite extended, embracing 10 courses, each occupying four years as follows: civil and topographical engineering, mechanical engineering, geology and mining engineering, building and architecture, chemistry, metallurgy, natural history, physics, science and literature, philosophy. The visitor who examines this display will see that the students are encouraged to make experiments and original investigations, and that a prominent place is given in most courses to the subject of drawing. This institution opens its doors to members of the gentler sex, and it is pleasing to find an account of some thorough analytical work by one of the female graduates. The school year is about 36 weeks, and the necessary expenses, including board and tuition, vary from $500 to $600 per school year."

"On a recent occasion, when all the Atlantic cables were interrupted except for the Direct, the entire business for two days was done on this one wire, and the average speed maintained for 48 successive hours was 10½ words per minute. The highest speed attained was 18 words per minute. The length of the cable is 2,500 nautical miles. This is the fastest ocean telegraphy ever executed on a cable of equal length."

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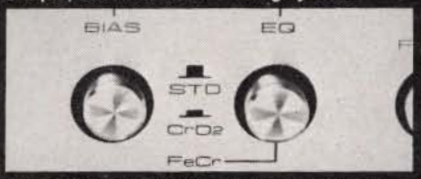


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# THE AUTHORS

NATHAN KEYFITZ ("World Resources and the World Middle Class") is Andelot Professor of Demography and Sociology at Harvard University. A Canadian citizen, he was graduated in 1934 from McGill University, where he majored in mathematics. He spent the next two decades working as a statistician for the Dominion Bureau of Statistics in Ottawa, meanwhile acquiring his Ph.D. in sociology in 1952 from the University of Chicago. His academic career began in 1959, when he was appointed professor of sociology at the University of Toronto. Before joining the Harvard faculty in 1972, he was professor of demography at the University of California at Berkeley. A specialist in the application of mathematics to the study of population trends, he has written several books, including *Introduction to the Mathematics of Population* (1968).

GEORGE A. COWAN ("A Natural Fission Reactor") heads the nuclear-chemistry division of the Los Alamos Scientific Laboratory. He writes: "I became involved with reactors as a research assistant at Princeton University in 1941, working with the group headed by Eugene Wigner on the neutron-capture properties of uranium. From there I went to Herbert Anderson's reactor-building group at the Metallurgical Laboratory of the University of Chicago, and then all around the Manhattan District laboratories during the war. I went back to school at the Carnegie Institute of Technology in 1946 and left in 1949, graduate work completed, to return to Los Alamos. Here I've been involved in many aspects of nuclear science based on the study of nuclear explosions. I am just now greatly intrigued by the information that can be obtained from a fossil reactor, particularly by the possibility that the Oklo investigation will demonstrate an acceptably safe pattern for the permanent disposal of plutonium."

BRUCE S. McEWEN ("Interactions between Hormones and Nerve Tissue") is associate professor at Rockefeller University, where he received his Ph.D. in biology in 1964. His undergraduate degree, in chemistry, is from Oberlin College. He joined the Rockefeller faculty in 1966, after working for a time as a U.S. Public Health Service postdoctoral fellow at the Institute of Neurobiology in Göteborg, Sweden, and as assistant professor of zoology at the University of Minnesota. In addition to his teaching and research McEwen currently serves on the editorial boards of seven professional journals in the fields of neurochemistry and behavioral biology. In his spare time, he reports, he enjoys playing tennis and the classical guitar.

JACK ROBERT MILLER ("The Direct Reduction of Iron Ore") is a consulting engineer and economist who has worked in the iron and steel industry for more than 30 years. He holds degrees in electrical engineering from the Cooper Union Institute of Technology, in economics from New York University and in metallurgy and mining from the National University of Engineering in Lima, Peru. (The last, Doctor of Engineering, was awarded in 1952 by a special act of the Peruvian government on the recommendation of the faculty.) His consulting work, which has taken him all over the world on some 40 overseas projects, ranges over many facets of the minerals industry, from the development of mines to the design, construction and operation of steelmaking plants. Besides working at one time or another for several major U.S. steel companies, Miller has served as a staff member of the United Nations Centre for Industrial Development, the World Bank, the Inter-American Development Bank and the Battelle Memorial Institute. In 1973 he was Visiting Battelle Professor in Metallurgy at Ohio State University. A long-time advocate of direct-reduction techniques, he has for the past few years operated his own consulting firm in Columbus, Ohio.

FREDERICK J. ALMGREN, JR., and JEAN E. TAYLOR ("The Geometry of Soap Films and Soap Bubbles") are mathematicians on the faculty of Princeton University and Rutgers University respectively. Their collaboration began a few years ago at Princeton, where Almgren is professor of mathematics and Taylor did her graduate work in mathematics. Now married, they note that although each has published a number of mathematical papers in recent years, the present article is their first joint one. Almgren majored in engineering as an undergraduate at Princeton, earning varsity letters in the pole vault and being graduated with highest honors. He served for three years in the Navy as a jet-fighter pilot before going on to graduate school at Brown University, where he acquired his Ph.D. in mathematics in 1962. He has been a member of the department of mathematics at Princeton ever since, except for several periods at the Institute for Advanced Study in Princeton and a sojourn as a National Academy of Sciences exchange visitor at the Steklov Mathematical Institute in Leningrad. Taylor, who was graduated summa cum laude with a degree in physical chemistry from Mount Holyoke College, has in addition two master's degrees—one (in physical chemistry) from the University of California at Berkeley and another (in mathematics) from the University of Warwick—as well as her Ph.D. in mathematics from Princeton. She taught mathematics for a year at the Massachusetts Institute of Technology before being appointed assistant professor of mathematics at Rutgers' Douglass College in 1973.

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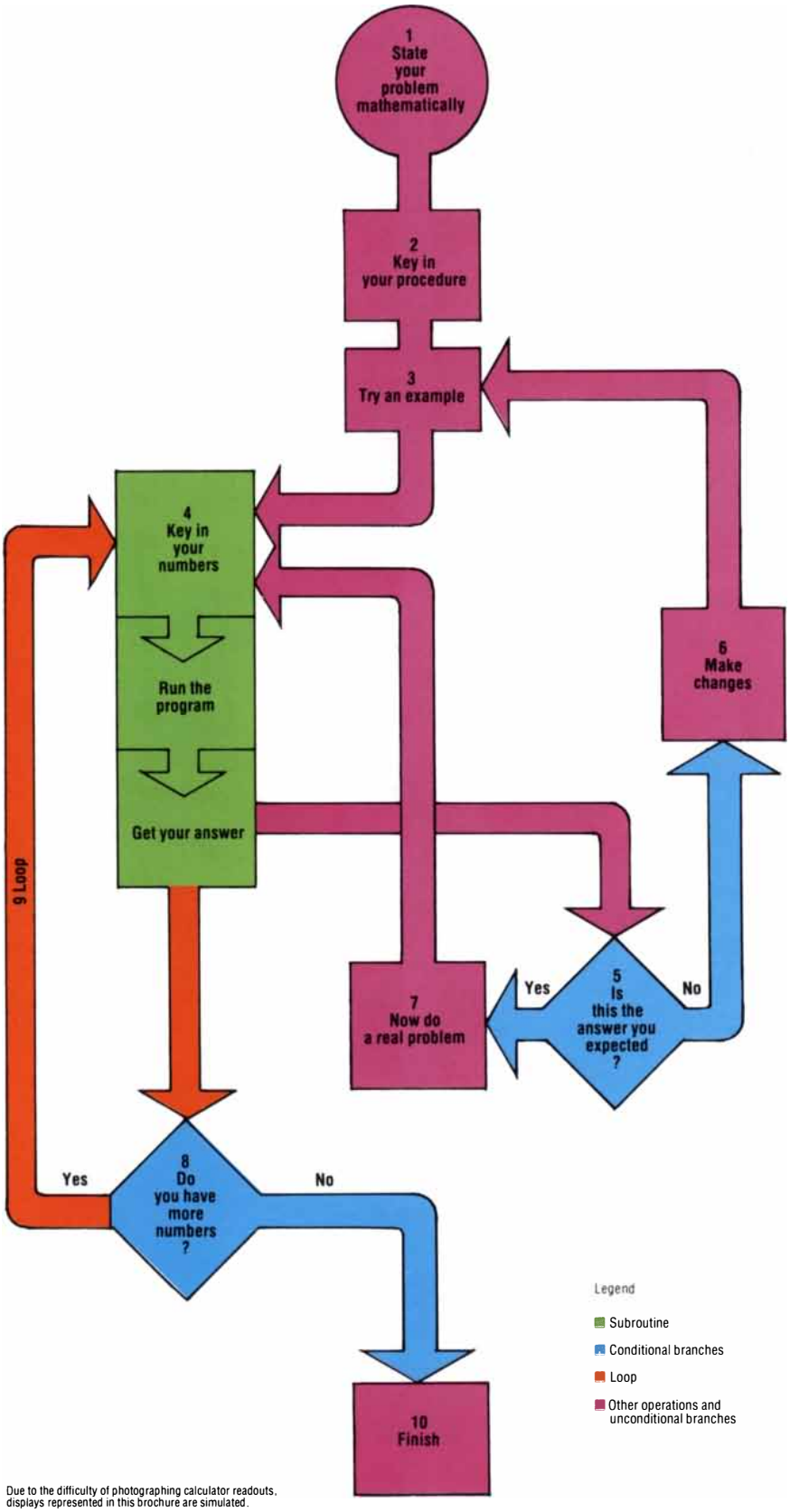


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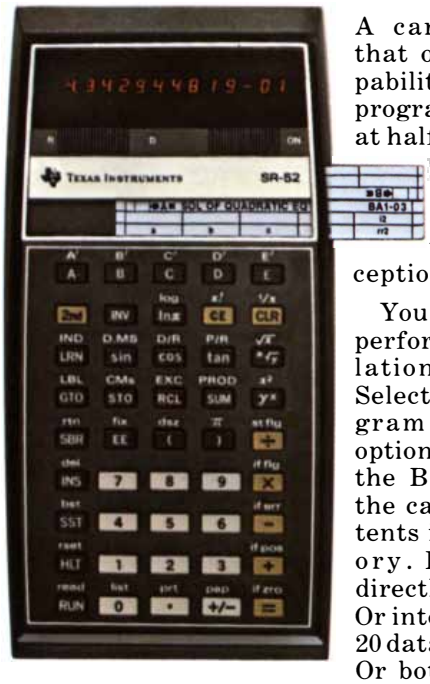


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**Learns your way of solving problems.** In just a few hours, you could be writing programs. Using its 224-step program memory, the SR-52 will handle programs you may have thought required a computer. Press LRN to store each following keystroke. Press it again and the SR-52 has learned your program. It's ready to RUN. Record your program on a blank magnetic card, and make it part of your personal library.

**Computer-like branching.** Offers three types of unconditional branching: Go to. Subroutine. Reset. And 10 conditional branches: Six display tests. Two flag tests. Two looping tests. Also, 10 user-defined keys.

**Direct or indirect access to 20 data memories.** Store numbers directly in memory registers. Or, store a number in a data memory specified by another register (indirect addressing). Add, subtract, multiply, divide within registers. Exchange display with memory.

**Edit and debug.** Move through a program a step at a time. Forward or backward. Insert. Delete. Or write over steps.

**Basic Library of 22 prerecorded programs.** Twenty-two prerecorded program cards come with an SR-52. You can put them to work right away. You also get a 96-page Basic Library manual. Each prerecorded program card is supported with sample problems, user instructions and program listings. See optional libraries on the back cover.

**• Conversions (1,2) • Solution of Quadratic Equation • Hyperbolic Functions • Prime Factors of an Integer • Complex Arithmetic • Checkbook Balancing • Compound Interest • Ordinary Annuity (1,2) • Trend Line Analysis • Permutations and Combinations • Statistical Means and Moments (1,2) • Random Number Generator • High Pass Active Filter • Low Pass Active Filter • Dead Reckoning • Lunar Landing Game • Diagnostics**

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Easily becomes an integral part of your work. As a powerful slide rule calculator that also does double-duty as an economical, powerful key-programmable. Capable of solving many problems handled by computers with its: 100 programming steps. Eight-register stack (handles up to seven pending operations). Nine levels of parentheses. And 10 data memories.

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**Unique independent test register.** Compare the value in the display with a value in the t-register – without interfering with processes in progress. If your test conditions are met, then a conditional branch takes place. Otherwise the sequence continues.

**10 memories to do your tough problems.** Store and recall data. Add, subtract, multiply or divide within a memory register. Without affecting the calculation in progress.

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**Easy editing.** Single-step and back-step keys let you sequence through program memory to examine what you've done. If you pressed a key incorrectly, you can go back and write over it (NOP).

**Also a powerful slide rule.** 74-pre-programmed functions and operations. Handles basic math. Logs and trig. Advanced statistical problems. Polar/rectangular conversions.

**An applications library, too.** A 192-page collection of programs. All pre-written. Select a program. Follow the listing (putting in your own data, of course). And, you'll immediately begin using your SR-56's computing power to solve your own problems.

Every program in the Applications Library was chosen specifically on the basis of occupational demands. Each program contains a thorough description of how it works and the conditions under which it operates. There are also extensive examples of each program in typical problem solving situations.

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*Suggested retail price.
†Based on suggested retail prices of models available at the time of this printing.

calculator a few years ago, Texas Instruments had a choice: algebraic entry or Reverse Polish Notation (RPN). TI chose algebraic entry because it's the most natural and easiest to use.

Now, with the new SR-52 and SR-56 programmable calculators, TI takes another major step forward in power and ease of use—the unique Algebraic Operating System.

## What is AOS?

**Actually, it's easier to use than to explain.** AOS is more than just algebraic entry. It's a *full* algebraic hierarchy coupled with multiple levels of parentheses. This means more pending operations, as well as easy left-to-right entry of expressions—both numbers *and* functions.

## Algebraic hierarchy.

This is the universally recognized order of performing calculations. Functions first. Powers and roots. Multiplication or division. Then addition or subtraction. AOS performs calculations in this order. But you have the option to change the order whenever you wish by using the parenthesis keys.

## Why pending operations are so important.

Because you can compute complex equations di-

tion like this:

$$1 + 3 \times \left[4 + \frac{5}{\left(7 - \frac{2}{9}\right)}\right] = ?$$

contains six pending operations as it's written. An SR-52 or SR-56 programmable calculator with full AOS easily handles it just as it's stated, left-to-right. You don't have to rearrange the equation, or remember what's in the stack as with RPN.

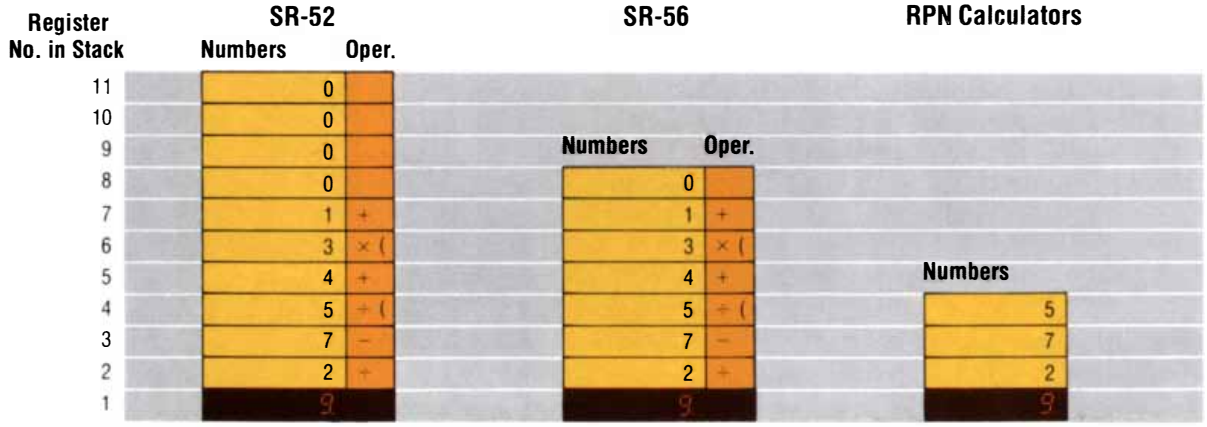
A calculator with "full AOS *remembers* both the numbers and functions in its register stack. And performs them according to algebraic hierarchy. As more operations become pending, the stack fills up (as shown in the diagram). Finally, when the equals key is pressed, the operations in the register stack are performed to give you the answer (15.21311475). Automatically.

## AOS makes the calculator part of the solution. Not part of the problem.

The case for AOS is strong. That's why TI uses it. Whether you own a calculator with ordinary algebraic entry, or RPN or no calculator at all, we think you'll prefer AOS. Because you begin using it immediately. There's no new language to learn. Even if you are conditioned to RPN, the added value and power of TI's programmable calculators with unique AOS is well worth the easy transition.

### Here's how AOS stacks up.

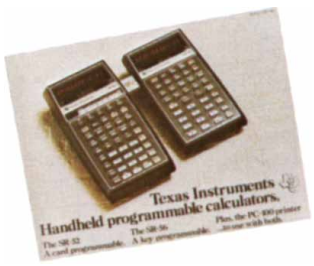
AOS remembers both numbers and operations, so you key-in your equation left-to-right.
RPN only remembers numbers, you have to remember operations and the order.




9 levels of parentheses
10 pending operations
11-register stack, including the display

9 levels of parentheses
7 pending operations
8-register stack, including the display

4-register stack including the display

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Circuit Design Engineer.

"I've developed a program that evaluates the output voltage of a saturated transistor buffer amplifier. It's a calculation that has to be iterated many times. The programmable can do it in seconds. It would take a good half-hour to do it by hand.

"I've got another program which is a real help in designing MOS transistors. I input the process parameters and the DC operating point. The programmable calculates the dimensions. We often use it in the lab to evaluate a prototype circuit. If we find out that one of the components is not up to spec, we can check the numbers and make an on-the-spot evaluation of the design."

**"I think its greatest value is the 'sensitivity' it gives you for variables."**
Wally Rhines.
Research Project Manager.

"I save trips to the computer. At my desk, I can say, for example, 'Ok, if I double the oxide thickness, what does it do to the capacitance?' Once I have a mathematical model, I can make any relationship I want.

"Off the job I use it to evaluate stock options using statistical modeling. I define my risks more accurately, then I can decide if I am willing to take them. I increase my sensitivity for the way stocks move—seeing instantly what would happen to my option if the stock should move up or down several points."

**"All I have to do is put in sales dollars. Then it computes: local tax, state tax, total tax."** Robbie Askew.
Accounting Supervisor.

"I used to figure these taxes manually. It took a good eight hours if I didn't have any interruptions. Now in an hour-and-a-half I am finished. The programmable does all the work."

**"I have instant turn around... examining different alternatives very rapidly... replacing intuition with insight."** Tony Barlow.
Systems Designer.

"In systems design you depend on how rapidly you look at alternatives. That's what determines your effectiveness. In one case—cost control in software development—I was able to examine more alternatives than I would have been able to examine in a week's time—or even a month's time. The result was the best understanding we ever had of the factors that influence software costs."

"And I'm having a ball using it for things at home—from photography to games and puzzles."

**"Now, because I can track complex contours with equations that generate NC tape data, we can develop more advanced tooling techniques."**
Harold Larsen.
Tooling Engineer.

"The advantage is that you can work with the numbers instead of going to the model shop for mockups, which are expensive. Writing a program cuts down turn-around time, since you don't have to go through all this. And with reduced lead time and longer tool life we can cut our costs dramatically without cutting back on quality."

**"We're getting yield improvements and therefore cost reductions. Because we can spot what's causing the problem quicker."** Bob Wolters.
Production Engineer.

"We're constantly running data reductions, evaluating yield and related process parameters. Before, it was all done by hand or on a big computer. Now, we're finding a lot more answers that are useful to us. Because the programmable calculator is right here. It's available. It's quick. A technician can do statistical correlations in a couple of hours where it used to take me all day.

"I also use a programmable in my hobby—amateur radio. I am technical director of the state VHF-FM relay league. We've developed test tables to increase the range of mobile units—extremely valuable in emergencies."

Imagine the convenience of getting a hard copy printout of: Data. Intermediate results. Answers. Imagine the efficiency of listing your entire program at the push of a key. Or, printing the calculator's entire data memory contents with a simple program. And now imagine seeing every step of your program as it's executed—both the number and the function. Imagine no more. TI's exclusive PC-100 printer is here. Ready to print ballistic trajectories or unit conversions. Complex tax analyses or simple cost/price margins.

## Optional libraries of prerecorded programs for the SR-52. $29.95*

**Math Library.** Hyperbolic functions, quadratic and cubic equations, simultaneous equations, interpolation, numerical integration, differential equations, matrix operations, base conversions, triangle solutions, complex functions, and more. 34 program cards.

**Electrical Engineering Library.** Active filters, resonant circuits, T-$\pi$ networks and transformations, transmission lines, phase-locked loops, transistor amplifiers, Fourier series, coils, power transformers, controlled rectifier and power supply circuits, and more. 25 programs.

**Statistics Library.** Means, moments, standard deviations, random numbers, permutations and combinations, t-statistics, analysis of variance, regression analysis (linear, power curve, exponential, logarithmic, quadratic), multiple regression, histograms, 12 distributions (normal, chi squared, Poisson, Weibull, hypergeometric, etc.) 29 programs.

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**More libraries on the way.** Navigation. Surveying. Aviation.

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| | | | | |
|---|---|---|---|---|
| Merged register ops. & comparisons | — | — | — | — |
| Program read/write on mag. cards | — | — | • | • |
| User defined keys | — | — | 10 | 5 |
| Possible labels | — | — | 72 | 15 |
| Absolute addressing | • | • | • | — |
| Subroutine levels | 4 | — | 2 | 1 |
| Program flags | — | — | 5 | 2 |
| Decrement & skip on zero (loop) | • | — | • | • |
| Conditional branching instructions | 6 | 8 | 10 | 7 |
| Unconditional branching | 3 | 1 | 3 | 2 |
| Indirect branching | — | — | • | — |
| Editing: Step | • | • | • | • |
| Backstep | • | • | • | — |
| Insert, delete | — | — | • | • |
| NOP | • | • | — | • |
| Single step execution | • | • | • | • |
| Pause | • | • | — | — |

| Operating characteristics | SR-56 | HP-25 | SR-52 | HP-65 |
|---|---|---|---|---|
| Logic System | AOS | RPN | AOS | RPN |
| Maximum number of pending operations | 7 | 3† | 10 | 3† |
| Parentheses levels | 9 | — | 9 | — |
| Memories | 10 | 8 | 20 | 9 |
| Store & recall | • | • | • | • |
| Clear memory | • | • | • | • |
| Sum/Subt to Memory | • | • | • | • |
| Mult/Div to Memory | • | • | • | • |
| Exchange display with memory | • | — | • | — |
| Indirect memory addressing | — | — | • | — |
| Exchange x with y | — | • | — | • |
| Exchange x with t | • | — | — | — |
| Fixed decimal option | • | • | • | • |
| Calculating digits | 12 | 10 | 12 | 10 |
| Angular mode Deg/Rad | • | • | • | • |
| Grad angular mode | • | • | — | • |
| Digits displayed (mantissa + exponent) | 10 + 2 | 8 + 2 | 10 + 2 | 10 + 2 |

†RPN Calculators only store numbers, while AOS stores both numbers and functions in its stack.

| Calculating characteristics | SR-56 | HP-25 | SR-52 | HP-65 |
|---|---|---|---|---|
| Log, ln x | • | • | • | • |
| $10^x$, $e^x$ | • | • | • | • |
| $X^2$, $\sqrt{X}$ | • | • | • | • |
| 1/X, $\pi$ | • | • | • | • |
| $y^x$ | • | • | • | • |
| $\sqrt[x]{y}$ | • | — | • | — |
| X! | •* | •* | • | • |
| Int X (integer part) | • | • | •* | • |
| Fractional part | • | • | •* | • |
| Trig functions & inverses | • | • | • | • |
| Hyperbolic functions & inverses | •* | •* | •* | •* |
| Deg/min/sec to decimal deg & inverse | •* | • | • | • |
| Deg to Rad conversion & inverse | •* | •* | • | •* |
| Polar to rectangular conversion & inverse | • | • | • | • |
| Mean, variance & standard deviation | • | • | •* | •* |

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larians") is assistant professor of biology at the University of California at Santa Barbara. A graduate of Carleton College, she obtained her Ph.D. in marine ecology from the University of California at Davis. Her main research focus, she writes, "is on the behavior and ecology of gelatinous zooplankton, particularly appendicularians, as studied through direct observation while scuba diving in the open ocean." Much of the work reported in her article, she adds, was conducted during a year's study of the Gulf Stream at the Lerner Marine Laboratory on Bimini in the Bahamas and in the course of similar expeditions in the Gulf of California. She is currently visiting the Australian Institute of Marine Science and is spending much of her time "on the Great Barrier Reef studying zooplankton endemic to coral reefs."

RÜDIGER WEHNER ("Polarized-Light Navigation by Insects") is professor of biology at the University of Zurich. A native of Germany, he was awarded his Ph.D. by the University of Frankfurt in 1967. Soon afterward he was invited to Zurich to set up a neurobiology group there. He has since spent two sabbatical leaves in the U.S. "far from my teaching and administrative duties in Europe": in 1973–1974 he was invited to work at Yale University and in 1975 he was a Rand Fellow at the Marine Biological Laboratory in Woods Hole, Mass. For the past few years Wehner has devoted his research to the study of the compound eye of hymenopterans such as bees and ants. He first became acquainted with the ants of the Sahara eight years ago. Although the ants are now bred in his laboratory "all year round," he notes that "each summer I enjoy staying, with my wife Sibyl, in the desert watching the foraging and homing behavior of the hunting ants in their natural habitat."

JOHN S. McNOWN ("Canals in America") is Albert P. Learned Professor of Civil Engineering at the University of Kansas. A Kansas alumnus, he also studied and taught at the University of Iowa and the University of Minnesota, receiving his Ph.D. from the latter institution in 1942. He was a member of the staff of the Institute of Hydraulic Research at Iowa from 1943 to 1951, when "on one of the early Fulbright waves" he went to the University of Grenoble, "where my hydraulic interests were widened to include inland navigation and harbors. These studies then broadened further to include old locks and canals, and I soon became a canal buff." In addition to his teaching, research and consulting in this country, McNown reports that he has "worked from time to time on developments in technical education in a score of the less developed countries under the auspices of the World Bank, UNESCO, foundations and various governments. I met my Swedish wife in Bangkok, and between business and pleasure we have visited waterways on all five continents."

Based on Road & Track magazine's consideration of hundreds of 1975 automobiles:

# The Rabbit is the best car in the world for under $3500.*

*Suggested 1976 retail price $3,499 East Coast P.O.E. (4-dr. model higher). Transportation, local taxes, and dealer delivery charges additional.
†Based on Agbabian Associates test results. ©Volkswagen of America.

## It wasn't Toyota.
## It wasn't Datsun.
## It wasn't Vega.
## It wasn't Pinto.
## It wasn't Honda.
## It wasn't Fiat.

We set our standards high.

So did the car experts of Road & Track.

In naming the 10 best cars in the world, they began with a subject dear to our hearts.

And we quote: "We considered value for money carefully. With what has happened to prices the last three years this is more critical than ever in America; no longer can so many of us buy on a whim and trade every two or three years."

The annual Detroit model-change madness is dying a well-deserved death.

The Volkswagen Rabbit was picked to be the best car in the world for under $3500 for the *right* reasons.

## 39 mpg highway, 25 mpg city.

These are EPA estimates of what the Rabbit achieved in the 1976 EPA tests.

The tests were performed with standard transmission. The mileage you get can vary, depending on how and where you drive, optional equipment and the condition

of your car.

No other car combines this kind of economy with the incredible power that moves a Rabbit.

## Beats Datsun outside.

You're propelled from 0 to 50 in only 8.2 seconds.

At that range, a Datsun B-210 is 60% slower than a VW Rabbit.†

If you've ever pulled out into a passing lane and then seemed to hang there as the seconds ticked away, you know the importance of this kind of pick-up.

## Beats Cadillac inside.

Looks are deceiving.

As Road & Track put it: "Its space for passengers and luggage is remarkable."

87% of the space in the Rabbit is devoted to functional room.

Open the large Hatchback, put the rear seat down, and you have more luggage space than in the trunk of a Cadillac Fleetwood.

There's as much glass area as you would find in a Lincoln Continental Mark IV and as much leg and head room as you would find in some mid-size cars.

All that, and it still parks like a Volkswagen.

## "First-class handling."

Road & Track said it.

So did our customers.

70% of the people who bought Rabbits said it was the test-drive that finally convinced them.

Front-wheel drive gives you better tracking, especially on wet roads.

Rack-and-pinion steering gives you better handling.

If one brake circuit fails, a second circuit takes over.

If one front tire blows, negative steering roll radius brings you to a sure, straight stop.

Safety package?

The whole car is a safety package, down to the padded key that fits into the ignition.

## VW Reliability.

Reliability, dependability —words often used loosely in advertising, were key to the Road & Track selection.

Today, over 1100 Volkswagen dealers are committed to making sure your Rabbit lives a long, happy, carefree life.

And they back this commitment with one of the most advanced car coverage plans in the automotive industry: The VW Owner's Security Blanket.

## Our Winner.

212 automobiles were considered.

10 won.

We at Volkswagen are proud to take our place next to the Mercedes-Benz 450 SE/SEL, the Porsche 911 Carrera, and the other fine cars chosen "The Best."

In this fast-moving, discountable, "move 'em off the lot and worry about service later" world, it's nice to know that something as seemingly remote as craftsmanship can still be appreciated.

The Rabbit

Established 1845 SCIENTIFIC AMERICAN July 1976 Volume 235 Number 1

# World Resources and the World Middle Class

*Economic development means entry into the high-consumption world middle class. In view of the limits that are set by world resources, only new scientific and technical knowledge can accelerate the rate of entry*

by Nathan Keyfitz

How much economic development is possible? Surely the planet and its materials are finite and not even all its present four billion people can live like Americans, let alone the six or eight billion that on present trends will be alive when a stationary world population is established. Indeed, there is doubt whether the 250 million people expected to populate the U.S. in the year 2000 will be able to live as Americans do today. How far, then, can industrial society spread through the preindustrial world before it reaches a ceiling imposed by space, raw materials and waste disposal?

That is the wrong question to ask, if human knowledge and capacity for substitution and the resilience of economic systems are unbounded, as they may well be. In that case the right question—and certainly a more tractable and pragmatic question—is how *fast* can development progress, whether toward an ultimate limit or not? What rate of technical innovation can be attained, oriented to allow a corresponding rate of expansion of industry, and how many of the world's people will that expansion enable to enter the middle class each year?

Attainment of the middle-class style of life is what constitutes development in countries as widely separated geographically and ideologically as Brazil and the U.S.S.R. In the process peasants gain education, move to cities and adopt urban occupations and urban patterns of expenditure. Changes are involved in people themselves, in where they live, in their kind of work and in the nature of the goods they consume. These changes can be visualized in terms of a definable line, comparable to the poverty line officially drawn in the U.S., across which people aspire to move. The pertinent questions then become: How many people are moving across the line each year, what is their effect on resources, at what rate can resources be expanded by new techniques and therefore what is the size of the window through which the world's poor will climb into the middle class during the remainder of this century and beyond it?

A main issue of development for many of the people of Asia, Africa and Latin America is how to enlarge that window into the middle class. Since, according to a generally accepted view, it is middle-class people who limit their families, the rate of movement into that class helps to determine the level at which the world population can be stabilized, and that level in turn will determine the degree of well-being that can be supported by world resources. And if shortage of resources makes the opening into the middle class as it is presently constituted so narrow that the majority will never be able to pass through it, then the sooner we know this the better. The Chinese rather than the Brazilian-Russian pattern of development may be what people will have to settle for.

The questions I have raised are difficult for many reasons, including the lack of statistical information, uncertainty about the capacity of productive systems to substitute common materials for scarce ones and uncertainty about the directions in which technology will advance. Some data and some pointers are available, however.

Let us begin with population. The world population, according to the United Nations estimates I shall be following, passed the four-billion mark in 1975. It had passed the three-billion mark in 1960. Whereas the last billion was added in 15 years, the first billion had taken from the beginning (one or two million years ago) until 1825. The growth has been far faster than exponential growth at a fixed rate of increase (as with compound interest); instead the rate rose from something like an average of .001 percent per year through the millenniums of prehistory to 1.9 percent through the decade and a half from 1960 to 1975.

Apparently the rate of increase will not rise further. The same 1.9 percent, according to the UN medium variant, will hold until 1990, and by the end of the century the increase will be down to 1.6 percent per year [*see illustration on page 30*]. Other estimates place the peak earlier and make the decline in rate of increase faster. Insofar as the increasing rate of increase constituted a population "explosion," we can draw relief from the fact that we are now down to "only" exponential growth. (This peaking was inevitable because of what mainly caused the rise to begin with: the decline in mortality during infancy and childhood. Mortality improvement after the reproductive ages does not affect increase much and in the long run does not affect it at all. Once the chance that a newborn infant will survive to reproduce itself gets up to about .90, the scope for further rise is limited, and whatever rise takes place will be offset by even a small decline in the birthrate.)

Those who worry about the population explosion can take some comfort in this peaking of the rate of increase, but not very much. Dropping to exponential growth still leaves the world population increasing (on the UN medium variant) by about 75 million per year now, with the annual increment rising to 100 million by the end of the century. And the absolute increase, rather than the rate, seems to be what matters. To feed the present yearly increment requires nearly 20 million tons of additional grain each year, which is more than the Canadian wheat crop and about the same as the crops

of Argentina, Australia and Romania taken together. To look after the annual increment of population on even a minimum basis is going to be difficult enough; the real issue, however, is not how many people can live but how many can live well.

Production of most things consumed by the world's people has been increasing at a higher rate than the 1.9 percent per year of population. During the period from 1960 to 1973 meat output increased at 2.8 percent a year, newsprint at 3.7 percent, motor vehicles at 6.8 percent and energy consumption at 4.9 percent, and the rise was similar for many other commodities. These numbers can be taken to mean that on the average mankind is year by year eating better and reading more, becoming more mobile and substituting machine power for the power of human muscles. Such a conclusion would seem to be confirmed by worldwide figures on productive activity or income. For example, adding up the gross domestic products of all countries for 1970 yields a gross world product of $3,219 billion, an average of $881 per head. The total has been going up at nearly 5 percent per year in real terms, that is, after price increases. Even allowing for the 1.9 percent increase in population, we seem to be getting better off individually at about 3 percent per year. Projecting on this basis, real goods per head would double every 23 years; each generation would be twice as well off as the preceding one. To dispose of twice as much wealth as one's parents, four times as much as one's grandparents, surely cannot be regarded as unsatisfactory; the world, such figures seem to show, is moving toward affluence. That conclusion requires substantial qualification.

The division of a total number of dollars by a number of individuals to obtain an average per head has a long tradition; dividing one number by another is an innocent operation and without any necessary implication that everyone obtains the average, and yet it puts thoughts into people's minds. The first thought might be that things are not bad with $881 per head for the entire global population—a conservative conclusion. The second thought might be that things would indeed not be bad if the total was actually divided up—a radical viewpoint that has been voiced often in recent years. Income is an aspect of a way of life, however, and only a trifling part of a way of life is directly transferable.

The fallacy of redivision is encouraged by putting income into terms of money and performing arithmetical division. To say we should divide income so that everyone in the world can have his $881 is to solve a real problem with a verbal or arithmetical trick, because behind the numbers is the fact that Americans live one way and Indians another way. If, starting tomorrow, Americans were all to live like Indians, then their higher incomes would simply disappear. There would be nothing to transfer.

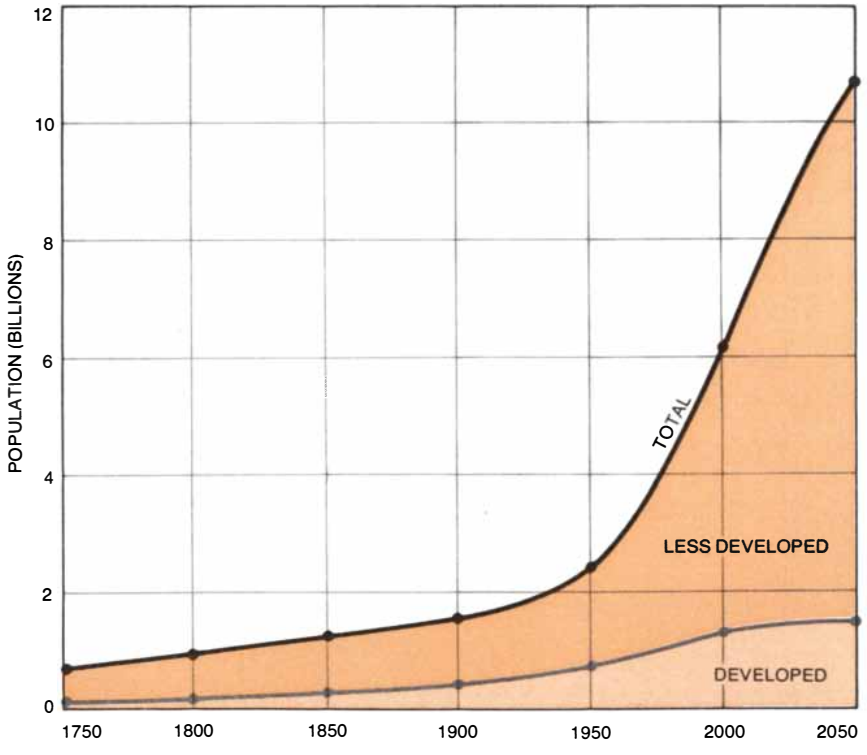
How much is transferable depends on the extent to which Americans could consume like Indians while continuing to produce like Americans. Simon Kuznets and others have pointed out that as soon as one tries to plan a transfer the tight bond between production and consumption frustrates the attempt. For example, the cost of travel to work is called consumption, but if people stopped traveling to work, production would fall to zero. What about the cost of holidays and entertainment, which are elements of consumption but which refresh people for further work? What about nutrition, education and health services? And what about the enjoyment of consumer goods that is the incentive to work and earn? All of these and many other parts of consumption feed back into production. Moreover, to discuss massive transfers of capital would be futile for political reasons even if it were economically practical: the declining U.S. foreign-aid budget shows how unappealing to the major donor this path to world development is.

Because the world population is heterogeneous, no style of life is in fact associated with the world average of $881. Following that average through time leads to the mistaken impression that things are getting better every year and will do so indefinitely. Even a two-way breakdown of the average is a major step toward realism.

Of the total world population of four billion estimated for 1975, 1.13 billion, or nearly 30 percent, live in developed countries. The fraction of the annual increment of population accounted for by those countries is much less, however: only 10 million out of 75 million, or 13 percent. The annual increment in the less developed countries is more than 65 million, and it will rise to 90 million by the end of the century (again on the UN medium estimates). This division of the world into two kinds of countries, rich and poor, or more developed and less developed, has become familiar since World War II. That world 1970 product (or income) of $881 per head is in fact an average of the developed countries' $2,701 and the less developed countries' $208.

Recent fluctuations obscure the long-term rates of increase, but suppose income for the rich and poor countries alike increases at 5 percent per year in the long term. On the population side, suppose the future increase is .5 percent per year among the developed countries and 2.5 percent per year among the less developed. Allowing for these population numbers brings the 5 percent annual gain in total product that was assumed for both down to about 4.5 percent for the developed countries and only 2.5 percent for the less developed ones.

The result is a widening gap between the two groups of countries, an exercise in the mathematics of geometric increase [*see illustration on page 31*]. Think of the developed countries starting at $2,701 per capita and increasing at 4.5 percent per year in real terms; after 25 years they have risen threefold, to a per capita income of more than $8,000 in 1995. By that time the income per




**"POPULATION EXPLOSION" CURVE is the result of more-than-exponential growth; the annual rate of increase has itself been rising, most sharply in the past century, largely because of the decline in infant and childhood mortality. In this layer chart the total population (projected to the year 2050 according to the United Nations medium estimate) is given for countries currently classified by the UN as "developed" (*light color*) and "less developed" (*dark color*).**

head in the less developed countries has not even doubled: their $208 has risen to only $386. By the year 2020 the grandchildren of the present generation will have, in the one set of countries, more than $24,000 per head and in the other countries the still very modest $715—one thirty-fourth as much as the rich, and not yet as much as the 1970 world average!

The calculation shows how a heterogeneous population is bound to develop a widening gap between rich and poor if per capita rates of increase are frozen. I have assumed that all national incomes increase at 5 percent per year. Overall national-income growth is not conspicuously different, on the average, for the poor and the rich countries, and so it is the differences in population growth that are decisive.

To speak of developed and less developed countries is an improvement on treating the world as being homogeneous, but it has been overtaken by the events of the past three years. Where two categories of countries once sufficed, we now find we cannot do with fewer than four.

The shifts in raw-material prices have created resource-rich countries such as Abu Dhabi and Venezuela, whose wealth is comparable to that of the developed countries, which by way of contrast can be called capital-rich. Some countries that were poor have actually been developing, including Singapore, Korea, Taiwan and Hong Kong. Finally there are the many countries that are truly poor, lacking (in relation to their population) both capital and resources. We have, then, the resource-rich countries, the capital-rich countries, the developing countries and the poor countries. Specifically identifying and classifying all cases to provide numbers for population in these groups is not easy. (Indonesia has resources but not enough so that any likely rise in prices would make its 135 million people rich.) The new categories of resource-rich and developing countries might be defined in such a way that they total 200 million people each; the fact remains that most of the world's people are in countries that have no leverage through either control of capital or control of resources.

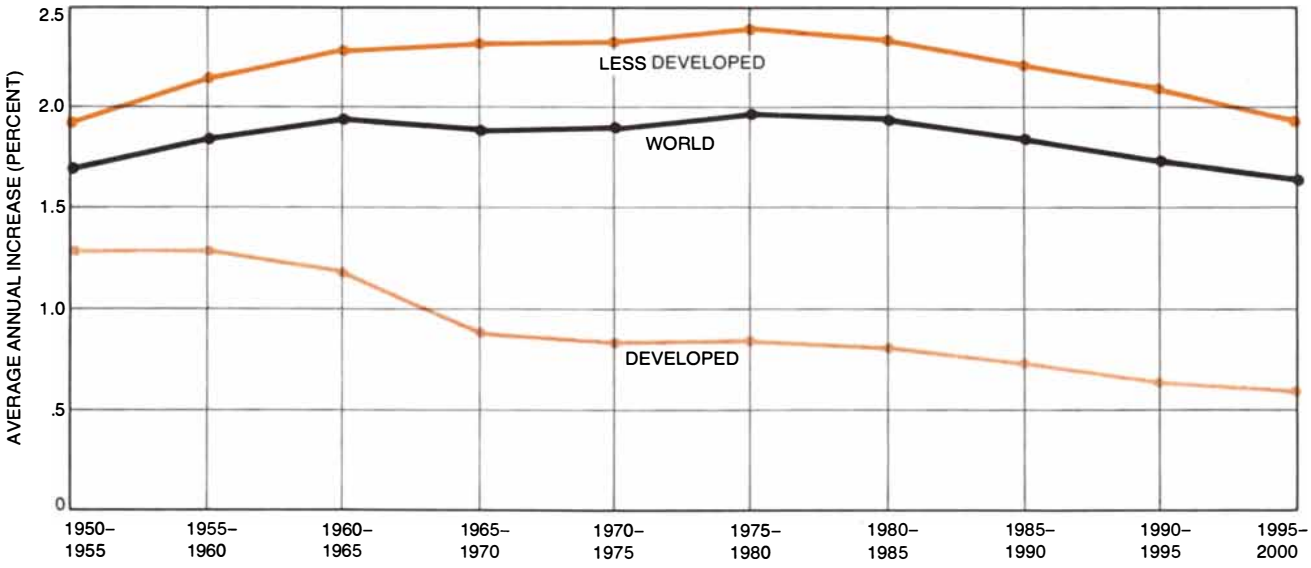
No country is homogeneous, however; the poorest countries contain some rich people and the richest contain some poor. Nations and their governments dominate our age so completely that individuals too easily drop out of political as well as statistical view, yet the welfare of governments is not a worthy ultimate objective; it is the people of the poor countries who deserve our concern. And so what follows will deal as directly as possible with people.

The typical poor person and the typical middle-class person are easy to visualize; the first is a peasant in Java, Nigeria, the Brazilian Northeast or elsewhere in Asia, Africa and the Americas; the second is a city dweller in San Francisco, Frankfurt, Leningrad or Tokyo with an office job that puts him well above the poverty line. There are less obvious representatives. Along with the peasant group one should count as poor the wage laborer of Calcutta or the urban unemployed of the U.S. And the middle-class group includes the unionized construction worker, the bus driver, the key-punch operator and the successful farmer in the U.S., Europe, the U.S.S.R. or Japan; that some of these are considered blue-collar is secondary to their earning a middle-class income.

In survey after survey most Americans, when they are asked where they think they belong, place themselves in the middle class. The self-classification by which most Americans tend to call themselves middle-class and Indians tend to call themselves poor accords with the distinction I have made. Most of those called middle-class in the world live in the cities of the rich countries, but some of them live in poor countries and some live in the countryside. The crucial part of the distinction is that middle-class people are in a position to make effective claim to a share of the world's resources that accords with modern living.

With an income measure of welfare, people fall on a continuum and the location of the poverty line is arbitrary. As a country grows richer its standards rise, so that the same fraction of its population may be defined as "poor" even as everyone in the country is becoming better off. In the case of the U.S., however, it has been possible to reach broad agreement on a Social Security Administration definition of poverty based on relatively objective criteria. An average urban family of four, including two children, is said to require $3,700 a year (at 1974 prices) to pay rent, buy clothing and meet basic nutritional needs, and similar levels are set for other types of household.

"Middle class" describes a style of life and can cover not only physical necessities but also such conventional needs as power lawn mowers and winter vacations in Florida. It needs to be specified separately for each culture before one can see how many people enjoy it and what the energy and resource consequences of the enjoyment are. Pending such a study I propose to call middle-class those who are above the equivalent of the U.S. poverty line, wherever they may live. Cultural differences make poverty in one country intrinsically noncomparable with poverty in another country, but they make average money incomes just as noncomparable. The effort to quantify important notions must not be prevented by some degree of qualitative difference; the fraction under the level of consumption represented by the U.S. poverty line is not the definitive way of measuring the world's poor, but it




**RATE OF INCREASE of population is apparently reaching a peak during the present half decade. The average rate of increase per year is plotted for five-year intervals for the developed (*light color*) and less developed (*dark color*) countries and for the world as a whole (*black*). The rate of increase turned down several decades ago for the developed countries and is expected to do the same thing soon in the less developed countries. The "explosion" is ending, in the sense that the growth of the world population will be less than exponential.**

will serve for the moment. In the U.S. that fraction was 11.6 percent in 1974, an increase from 11.1 in 1973 but a decrease from 22.4 in 1959. Of the U.S. population of 210 million in 1973, some 23 million were poor; call the remaining 187 million middle-class. Let us try to find indexes that will provide a corresponding number for other countries.

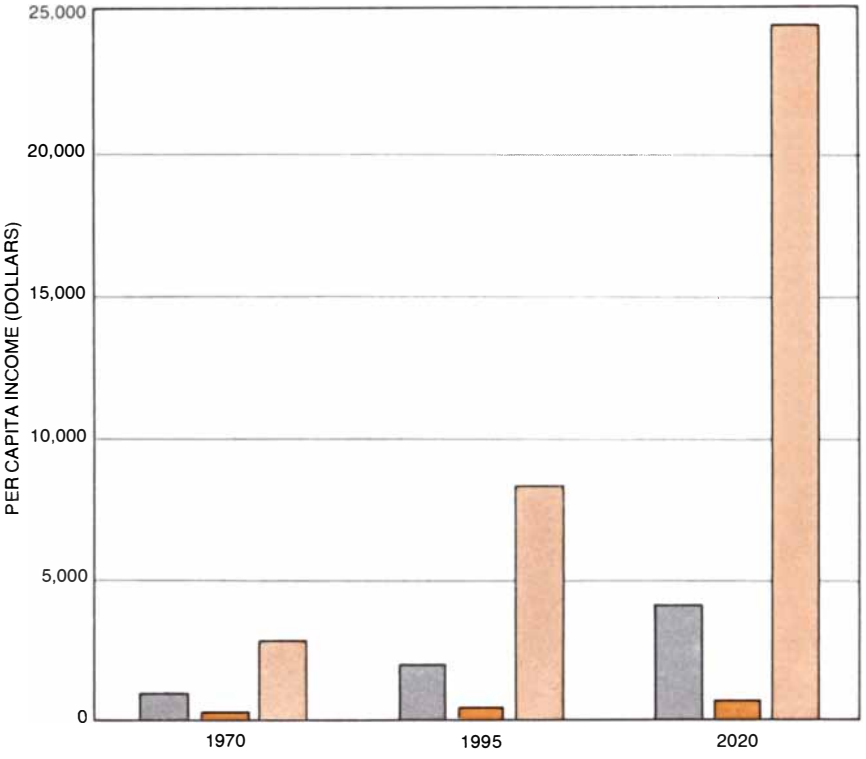
Passenger cars in use might be taken as roughly proportional to the middle-class, or above-poverty, population. In the U.S. in 1973 the number of passenger cars was 101 million and in the world as a whole it was 233 million, a ratio of 2.3. Insofar as the 233 million passenger cars in the world are being driven and ridden in by a world middle class, we can multiply the U.S. middle class of 187 million by 2.3 and derive a world total of 430 million middle-class people. This number is too low, because automobiles are less a part of daily life even in other affluent countries; we know that trains continue to be used in Europe for much travel that is done in the U.S. by automobile.

Let us try telephones as the indicator. The world total in 1973 was 336 million telephones and the U.S. total was 138 million. On this index the world middle class was 187 million times 336/138, or 455 million. With electric energy as the indicator a similar calculation gives a world middle class of 580 million. Each one of these indicators is surely defective. One can nonetheless hope that their defects are more or less constant over the 20 years or so that I propose to apply them to establish a trend.

A slightly different way of doing the calculation is to take it that modern living requires about four metric tons of crude oil a year for heating, air conditioning and motoring, so that the world output in 1973, 2,774 million tons, could cover the needs of 700 million people. (The calculation is approximate because some poor people do use a little oil and large supplies go to military and other government uses.)

Averaging the several approaches gives a world middle class of 500 million for 1970. What is important is that the corresponding average number—indexed on automobiles, telephones, electric energy, oil and other items—was something like 200 million for 1950. That indicates an average increase of 4.7 percent per year in the world middle class: the workers, and their families, who are integrated into industrial society, utilize its materials as the basis of their jobs and apply their incomes to consume its product. In doing so they have an impact on resources and on the environment. Just how great is the impact of change in status from poor to middle class, particularly compared with the effect of population change?

Raw materials are used by people, and so, if all else is fixed, the drain on resources must be proportional to the number of people. If each year the world population is 1.9 percent larger than it was the year before and nothing else changes, then each year resources are claimed by 1.9 percent more people, and in the course of 37 years we shall be on the average twice as dense on the land and shall be consuming twice as much iron and other metals and twice as much crude oil. This statement is not true of pollution, where more-than-proportional effects enter. It is true of resources insofar as technology for production and patterns of consumption both remain constant.

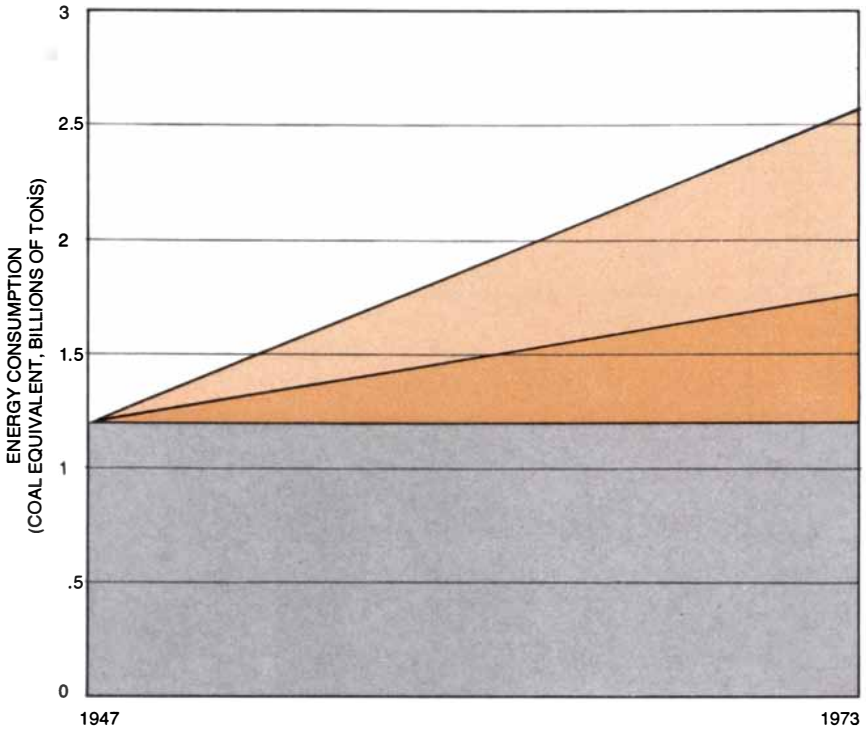



**WIDENING GAP between per capita incomes in the developed and in the less developed countries is caused by the more rapid growth of population in poor countries. UN figures for the developed (*light color*) and less developed (*dark color*) countries and for the world as a whole (*gray*) were projected on the assumption that total income will continue to increase at 5 percent per year in both sets of countries but that the population of the developed countries increases at only .5 percent per year while that of less developed countries increases at 2.5 percent.**

Actually they do not remain constant; they exert effects in opposite directions. Technology has been stretching the use of materials. We know how to put the tin on the can more thinly; we can make rubber and fabrics out of coal; we recycle aluminum. The movement, guided by price changes, is always toward less scarce materials. As income goes up, however, per capita consumption increases: more cans are used, albeit each with a thinner layer of tin. Worse still, new materials are invented—detergents, plastics, insecticides—that take a long time to reenter the cycles of nature once we are through with them. It is the net effect of these tendencies that we need to estimate.

One way to get at the net effect of increased consumption per head and of technological improvements is to determine the residual change after population increase is allowed for. Let us try this for energy consumption in the U.S. in 1947 and 1973. The 1947 consumption was 1.21 billion tons of coal equivalent and the 1973 consumption was 2.55 billion. Meanwhile the population rose from 144 million to 210 million. If the larger population of 1973 had held to the same volume and patterns of consumption and production as the smaller population of 1947, it would have required 1.77 billion tons of coal equivalent. Hence of the total increase of 1.34 billion only .56 billion was due to population growth; the remainder of the increase, .78 billion, was due to affluence. Affluence was more important than population [*see illustration on next page*]. Similar calculations can be made for metals and other materials, for pollution, for the primary caloric content of food, indeed for any kind of impact that can be measured.

As an alternative way of analyzing the consumption of materials, consider that from 1950 to 1970 the part of the world population that was affluent went from 200 million to 500 million: while total population increases at 1.9 percent per year, middle-class high consumers increase at 4.7 percent. Each high consumer requires the equivalent of three-quarters of a ton of grain, whereas the poor get by on a quarter of a ton. (The consequent ratio of land use is less than three to one, because agriculture is more efficient in rich countries.) The middle-class person requires from 15 to 30 barrels of oil, whereas the poor person makes do with one barrel at most in the form of kerosene, bus fuel and fertilizer. The land and energy content of clothing may be in a rich-to-poor ratio intermediate between those for food and for transport. As a kind of average of these several ratios, suppose the




**U.S. ENERGY CONSUMPTION would have increased from 1.21 billion tons of coal equivalent in 1947 to 1.77 billion tons in 1973 if it had merely kept pace with the rise in population. In fact, however, energy consumption rose to 2.55 billion tons in 1973. The increment (*light color*) due to a rise in per capita consumption stemming from affluence was larger than the increment (*dark color*) attributable to population growth. The same is true of many other materials.**

middle-class person has five times as much impact on the material base as the poor person. Then the average person on the high side of the poverty line must be taken as being equivalent to five people on the low side in fuel and metals consumed. In considering impact we therefore calculate as though in 1975 the planet had not four billion people aboard but 6.4 billion. Of these, 3.4 billion were poor and three billion represented the fivefold impact of a world middle class that probably numbered 600 million.

This would make the average total impact of the small middle class on resources somewhat less than that of the large number of the poor. The middle class has been increasing at 4.7 percent per year, however, and the poor less than half as fast. At the growing edge the increase of affluence has much more effect than the increase of population; the movement of people into the middle class has more effect on materials and the environment than the increase in the number of poor people.

Indeed, it has so much effect that if the population explosion is now ending (in the sense that the world rate of increase is peaking at 1.9 percent per year and starting to decline), we now face another explosion. It arises from the arithmetic of combining two exponentials, which is to say two progressions (population growth and middle-class growth) each of which has a fixed ratio.

The effect can be expressed in stylized form by supposing the 1975 population of four billion projected forward in the ratio 1.6 every 25 years (equal to the fixed rate of 1.9 percent per year). Suppose at the same time that the middle class triples every 25 years (equivalent to a fixed 4.5 percent per year), as it did from 1950 to 1975. The poor population is the difference between the resulting numbers. If the people above the poverty line average five times the impact of those below it, then we must add five times the middle class to the number of poor for the total impact. The result is a steadily increasing rate of increase of the impact, from 2.7 percent per year in 1950–1975 to 3.1 percent and then to 3.5 percent [*see illustration on opposite page*]. This is based on continuance of 1950–1970 rates of economic development and of population growth. Population growth will slow down, but that will not greatly reduce the impact, which in this illustration would be increasingly due to affluence. Our difficulties in maintaining the population and affluence levels of 1976 suggest that this model will not work. We cannot hope to keep tripling the middle class every 25 years. The main reason is shortage of resources.

Natural resources account for only about 5 percent of the value of goods and services produced in the U.S. and other developed countries. Resources are hence curiously two-sided: extracting them accounts for only a small part of the cost, yet they are the sine qua non of existence, to say nothing of progress. And particular materials do run out. England's Industrial Revolution was in part a response to a firewood crisis: cheap coal was substituted for wood, which had become scarce and very dear. In America, on the other hand, wood was cheap and labor was dear, so that houses were built of wood rather than stone, which is more labor-intensive. Now timber is dear here also, and masonry and aluminum are substituted in some products. Plastics take the place of paper in packaging. Cultivated southern pine is used for newsprint instead of the limited pine and spruce of the northern forests.

Thus history shows the resilience of the productive system, its ability to substitute commoner materials for scarce ones. Nevertheless, the extrapolation of this capacity must take account of time. Invention, innovation and capital replacement can proceed only at a certain pace. It is this pace of innovation that needs to be studied, since it sets the rate at which industrial society can spread in the face of environmental and resource limitations.

Limits to the spread of industrial society under present technology are suggested by the record of trade in raw materials over the past quarter-century. To take one example, in 1950 the production and consumption of energy were in virtual balance for the developed countries as a whole. Their deficit amounted to less than 4 percent of consumption. By 1973 production in the developed countries had nearly doubled but consumption had far outrun it and the deficit had swollen to a third of consumption.

The story for metals and other resources is not very different. No country, developed or not, has been provided by nature with a greater quantity and variety of mineral and other resources than the U.S. Yet even the U.S. had become a net importer of minerals by the 1920's, and it now imports all its platinum, mica and chromium, 96 percent of its aluminum, 85 percent of its asbestos, 77 percent of its tin and 28 percent of its iron—to select from a long list. Of course, the shortages of some of these minerals are not absolute but are a matter of price. The U.S. could produce all the aluminum it needs from domestic clay, but bauxite from Jamaica is cheaper. Having virtually exhausted the iron ore of the Mesabi Range, the U.S. resorts to lower-grade domestic taconite and to imports, in a proportion determined by prices.

The increase of more than 4 percent per year in the number of middle-class people who have come on the scene is too rapid in that these high consumers have to comb the world for resources, but on the other hand it is much too slow to satisfy the billions of people who are waiting in the wings. Whereas Europe, Japan and the U.S.S.R. have made great gains during the UN Development Decades, most of Asia and Africa are dissatisfied with their progress. Moreover, a realistic calculation would probably show a larger gap between the impact on resources of those who have raised themselves from poverty and that of those who are still poor. The weight of a middle-class person is in many respects more than five times that of a peasant. It is to keep the argument conservative that I suppose

the ratio is five times and that the world middle class triples every 25 years.

The combination of these two modest assumptions produces, as we have seen, a surprisingly high measure of impact for the end of the century, by which time the middle class, which was at 600 million in 1975, would increase to 1.8 billion and have the effect of five times that number, or nine billion. The total impact projected to the year 2000 is, then, that of nine billion plus 4.6 billion poor, or 13.6 billion people. This compares with an impact of 6.4 billion for 1975, calculated in the same way. If strains are already apparent in materials and energy, what will happen with a doubling of the rate of consumption?

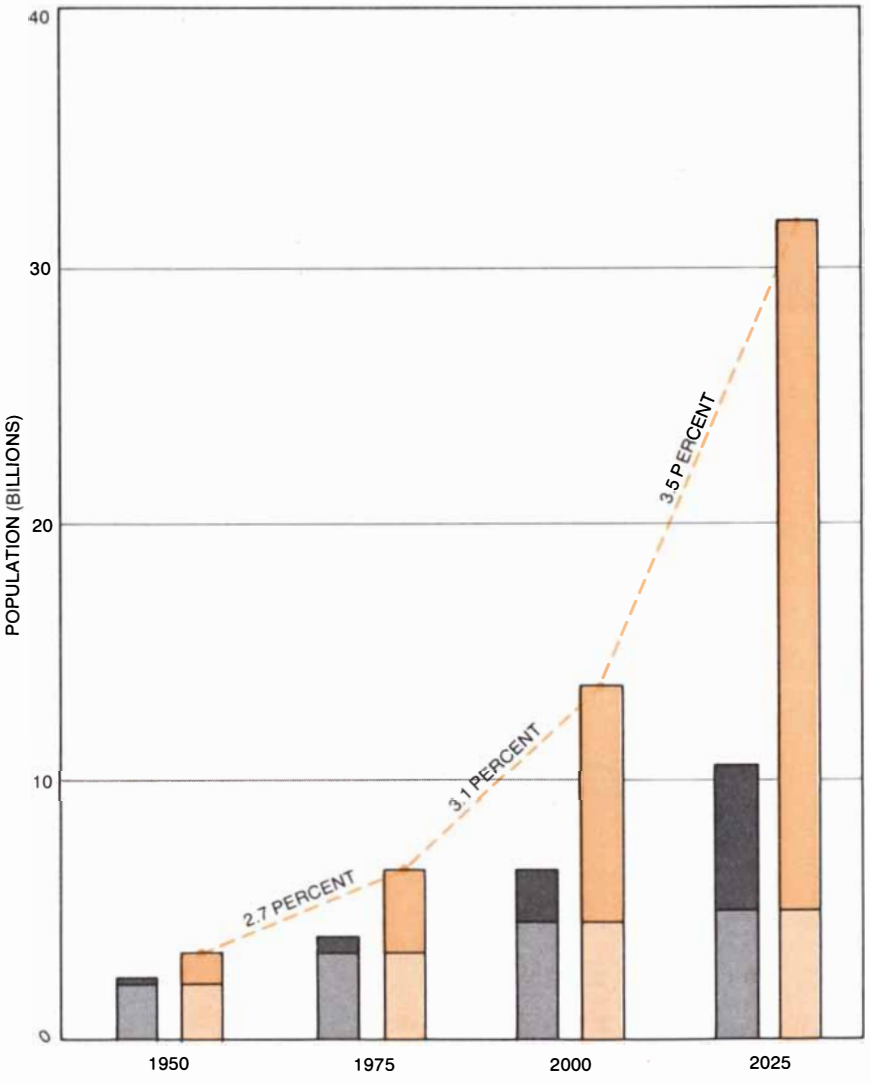
The accelerating impact that appears from recognition of two categories of people rather than one category is offset in some degree by the decline in the impact per dollar of income once income rises beyond a certain level. People take very high incomes in services rather than in more and more automobiles. Moreover, the relation of impact to income varies from one culture to another, as an anthropologist would point out; an economist would add that the relation can be counted on to change as raw materials, and hence the goods made from them, become scarce and costly compared with less material-intensive forms of consumption. Although the impact on materials may taper off with increased wealth, the impact on air and water may be greater than proportional. There may be thresholds: the air may hold just so much carbon monoxide, a lake just so much fertilizer runoff, without undue effect, but beyond a certain critical point the effect may quickly rise to disaster levels. Such critical points clearly exist in renewable resources. Fishing or cutting timber up to a certain intensity does no damage at all, but continued overfishing or overcutting can destroy the fish or tree population.

The rate and direction of development of the period 1950–1970, unsatisfactory though it may be in that the absolute number of the poor would continue to increase until well into the 21st century, is still faster than can be sustained on present strategies. The resilience of the economic system, and technical innovation in particular, can be counted on to respond to needs, but only at a certain rate of speed. One can imagine sources of energy, the capacity to dispose of wastes and substitutes for metals all doubling in the century to come, but it is not easy to conceive of such a doubling in the 15 years that would keep the middle class growing at 4.7 percent per year.

To say that civilization will collapse when oil supplies are exhausted, or that we will pollute ourselves out of existence, is to deny all responsiveness and resilience to the productive system. The geologist or resource expert tends to focus on the material and technical process he knows and may be less than imaginative with regard to how a substitute might be found to deal with a shortage. On the other hand, the economist may be too imaginative; he may too readily suppose substitutes can be found for anything as soon as it becomes scarce. The ensuing debate between pessimistic raw-material experts and optimistic economists has generated whatever knowledge we have on the subject. The middle ground to which both sides are tending is that every barrier that industrial expansion is now meeting can be surmounted by technological advance, but not in an instant. It is not a ceiling on total population and income that we have to deal with but that window. How large can the window be made?

One conclusion to be drawn from the arithmetic I did above is that a projection in terms of ratios is probably wrong in principle; in the face of natural and human limitations the pace of advance may be determined in absolute numbers rather than ratios. If, for example, pollution effects are proportional to fuel burned, then successive absolute increments in fuel consumption have the same bad effects on the fixed volume of the atmosphere. We should think not of the percent expansion of the middle class but of its absolute increase.

The calculation made in this way starts with the annual growth in world population of 75 million at the present time, gradually increasing to 100 million by the end of the century, and compares that increment with the number annually emerging into the middle class. If the latter went in a straight line from 200 million in 1950 to 500 million in 1970, then the average annual increase was 15 million. My stylized model, wherein industrial society expands through the emergence of people from the peasantry into city jobs as capital expands (while those not yet called remain at their old peasant incomes), goes back ultimately to Adam Smith. This simple application of the Smith model suggests that currently 15 million people join the middle class each year and 60 million join the poor. Even if the middle-




**FUTURE IMPACT on world resources is affected by the growth of the middle class, whose members are assumed to consume five times as much as poor people. In population alone the middle class (*dark gray*), increasing at 4.5 percent per year, would eventually be larger than the poor population (*light gray*). When the middle class is multiplied by five, the resulting "consumption population" (*color*) is seen to grow at an annual rate that increases from 2.7 to 3.1 and then to 3.5 percent. World resources are already strained by the 1975 "consumption population."**

class increment could rise to 20 million per year, the poor would still be increasing by 80 million per year at the end of the century. This at least is one reasonable extrapolation of the process of development in the postwar period. Other population estimates are lower than the UN's, but accepting them would lead to the same result: the large majority of the new generation will be poor. Therein lies the harm of rapid population growth.

The natural increase of the affluent population will create difficulties in the years ahead even though birthrates are low. Suppose the window is wide enough for 20 million to pass through it each year. Who will they be? The way the world is made, the children of the currently affluent of America, Europe and Japan will have first claim. The U.S.S.R. has found no way of preventing its elite from placing their children in the elite, and neither has the U.S. On the basis of 600 million for the middle class in 1975, a net natural-increase rate of .5 percent means three million children per year in excess of deaths. Apart from children who simply replace their parents or grandparents, of the 20 million net admissions each year three million would be further children of those who have already entered the middle class and 17 million would be new entrants. And these 17 million new entrants would be divided among the poor of the developed countries and those of the less developed countries, with the former having the better chance. Poor people in the poor countries sense that the odds against them and against their children are great.

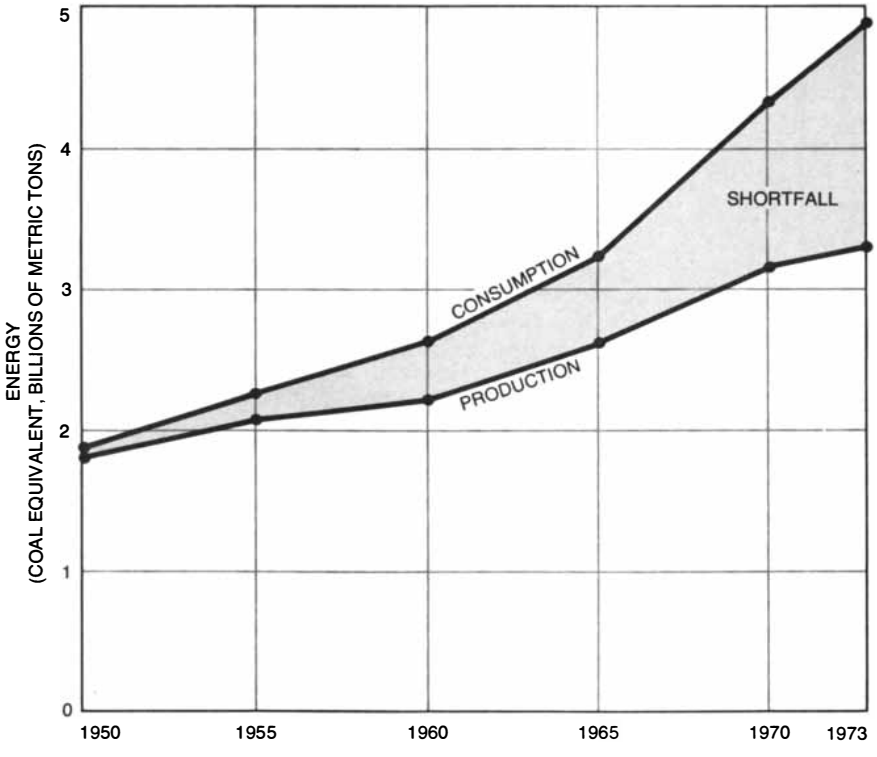
All of this, it should be noted, can be seen as a critique not of development but of one particular model of development. The distinction between poor and middle-class represents the Brazilian and the Russian direction but not the Chinese. Whether because of China's special culture or the personality of Mao Tse-tung, both the specialization that equips people for middle-class jobs and the durable structures of industry and administration in which those jobs have their place have been insistently denied there. It is asserted that everyone can do everything, that people ought to take turns working as peasants, driving trucks and being scholars; people need only so much to eat, to wear and to live in, and consumerism beyond that austere minimum is vice, not virtue. Whether this view can spread among other cultures and without a regime of the same type is not clear. There is little present sign of its spreading even to India, let alone to Japan, Europe or America.

Thomas Malthus gave us a land theory of value, Karl Marx a labor theory and development economists since World War II a capital theory. Land, labor and capital are plainly all needed (and to assign priority to any one may be as much an ideological choice as a practical one), but a dynamic factor superimposed on all of them is new scientific and technical knowledge. At many points we need to know more in order even to discover the problems we face: only recently have we found out that insecticides can be dangerous poisons to organisms other than insects, and that the current worldwide rise in skin cancer may be related to depletion of the ozone layer of the upper atmosphere. Knowledge is needed even to see where the window restricting passage into the middle class is located, and only knowledge can open it wider.

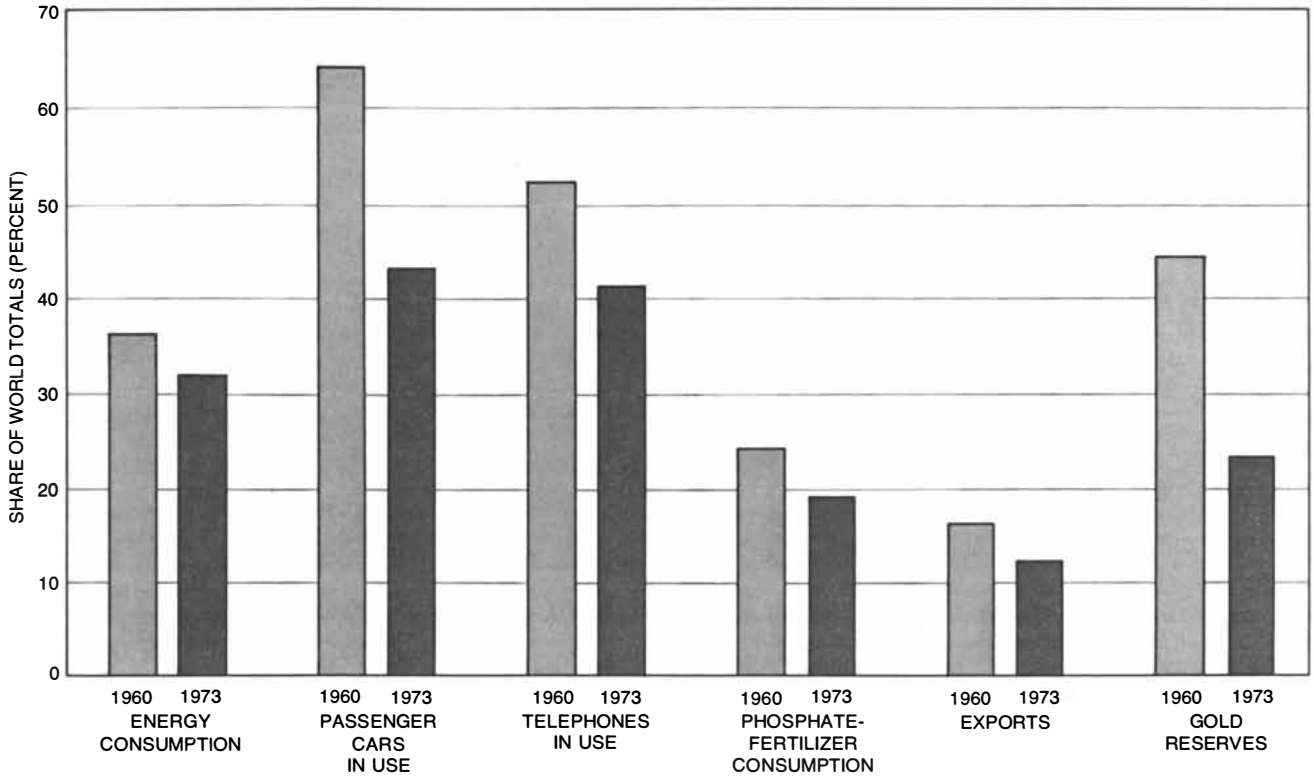
Other ways of widening the window have been suggested. One is to raise the price of the raw materials on whose export some less developed countries depend for foreign exchange. Price increases such as those of the Organization of Petroleum Exporting Countries (OPEC) can have little overall effect, however, on the number of middle-class people in the world (although they have some effect on whether the newly middle-class will speak Spanish or Arabic or English). Who ultimately bears the burden of such price raises is not clear. Some of the burden is carried by poor countries that are not endowed with raw materials; when the repercussions have worked themselves out, India may find it has contributed a higher proportion of its income to Saudi Arabian opulence than the U.S. has. Certainly some U.S. fertilizer that would have gone to India before 1973 now goes to the Middle East; German chemical-plant investments are similarly diverted. The offsetting of oil price rises by French arms sales to Iran has everything to do with national power and little to do with the total distribution of poverty or even the national distribution. The main point is that only a small fraction of the world population is in resource-rich areas.

A second way to help more people escape from poverty might be for those who have already entered the middle class to moderate their consumption. In principle, if one meat eater cuts his consumption, then five grain eaters can increase theirs. If American automobiles were smaller, more metals and fuels would be available for automobiles in Zaïre and Bangla Desh as well as—more immediately—fertilizer plants in those countries. If urban Americans were to live like the equally affluent Swedes, U.S. energy consumption might be halved. The trouble is that goods, as well as jobs that require materials, fit into other social activities in an interlocking scheme that is hard to change; social configurations are as solid a reality as raw materials. After two years of talking conservation, the U.S. consumes as much fossil fuel as ever. Faced with a world shortage of raw materials, every person of goodwill wants to see wasteful practices reduced, but the intrinsic limits on transfers I mentioned at the outset and the enormous inertia stored in producing and spending patterns make reduced consumption an unlikely way for the U.S. to help the poor countries.

Foreign aid and investment along conventional lines are a third possibility, but they have been disappointing. They have aided in the development of some countries (Canada is a striking example), but for various reasons the volume is inadequate to the magnitude of the problem for most of the




**CONSUMPTION AND PRODUCTION of energy were about balanced in 1950 in the developed countries: they produced the coal, oil, gas and hydropower whose energy they consumed, except for a small shortfall made up by imports from less developed countries. By 1973 rising production had been outstripped by consumption; shortfall amounted to a third of consumption.**




**INCREASE IN AFFLUENCE outside the U.S., particularly in Japan and Europe, has reduced the disproportionate U.S. share of energy consumption, durable goods and other indicators of wealth. Movement of more people across the poverty line would extend this effect.**

world's population. Even where investment is solidly based in economics some intellectuals argue that it creates dependency, and the politicians of poor countries often respond by expropriation. Ironically the very mention of expropriation is expensive for the poor country because it makes investors demand a higher return.

One can say that better prices for raw materials, reduction of consumption by the rich countries and conventional foreign aid and foreign investment all ought to be pursued, but the experience of the 1950's and the 1960's shows that they will not make a decisive difference in the size of the window through which escape from poverty is sought.

What will make a decisive difference is knowledge: of how to produce amenities with less material, how to substitute materials that are common for those that are scarce, how to get desired results with less energy and how to obtain that energy from renewable sources rather than from fossil fuels. We have seen some results in the past decade. With the advent of integrated circuits, a calculator that cost $1,000 and weighed 40 pounds is now replaced by one that costs $10 and weighs a few ounces. Artificial earth satellites have lowered the cost of communication; they provide television in Indian villages and may ultimately make telephone calls around the world as cheap as local calls. Synthetic polymers have replaced cotton and wool and thus released land. The list of what is still needed is too long to itemize: efficient solar collectors, compact storage batteries to run automobiles on centrally generated power, stronger and cheaper plastics (for automobile bodies, for instance) and so on.

If the time dimension in the implementation of these inventions is crucial, then everything that is done to hasten invention will pay off for the world movement past the poverty line. There are many stages, from pure scientific investigation to the translation of science into technology, to the engineering that makes a production model out of a working prototype and finally on to parts contracting and the assembly line, and each stage takes time. The U.S., once foremost in the speed with which it could convert knowledge into the production of goods, is said to be losing this preeminence; a slowing down would have bad consequences not only for the American competitive position among industrial nations but also for the world escape from poverty. The need is not confined to scientific and engineering knowledge; prompt solutions are also required of many problems in biology and medicine, climatology and geophysics. The technical and social knowledge for birth control is of special importance; whatever the size of the window through which the poor escape into the middle class, the lowering of births will at least bring closer the day when world poverty ceases to increase in absolute amount.

Some part of American research has been directed specifically to labor-intensive devices suited to poor countries, and that line of investigation ought to be encouraged. Even after the Green Revolution, for example, poor countries still have special agricultural problems. Apart from such specific research, the U.S. helps all countries when it develops knowledge that makes its own industry more efficient.

A particular preoccupation of the less developed countries is dependency; even commercial indebtedness is seen as neocolonialism. The technical evolution of the poor countries along lines suited to their own needs will be aided by American expansion of knowledge in that it will widen the choice of techniques available to them. In order that any such American contribution not create commercial indebtedness, it would be advisable to place the new knowledge and inventions in the public domain as the common possession of mankind rather than in patents on which royalties could be drawn.

Both production constraints and environmental constraints limit the growth of the world middle class. The way the U.S. can help to open the window is not through schemes for division of the existing product but by contributing knowledge that will expand the product. Solving production and environmental problems starts at home, but any genuine contribution will have value worldwide. Incentives can be devised to direct technology in environment-saving rather than environment-damaging directions. No one can forecast how much time it will take to solve any one technical problem, let alone the complex of problems, but that time—whatever it may be—will be shortened by a larger and more immediate mobilization of scientific and engineering talent.

# A Natural Fission Reactor

*Two billion years ago in west Africa a rich deposit of uranium ore began operating as a nuclear reactor. Long dormant but preserved intact, the reactor came to light during the mining of the deposit*

by George A. Cowan

In 1942, when Enrico Fermi and his associates started up their nuclear-fission reactor at Stagg Field in Chicago, there was every reason to believe it was the first such reactor on the earth. The record book must now be corrected. In an open-pit uranium mine in the southeastern part of the Gabon Republic, near the Equator on the coast of West Africa, are the dormant remains of a natural fission reactor. Within a rich vein of uranium ore the natural reactor once "went critical," consumed a portion of its fuel and then shut down, all in Precambrian times. The experiment at Stagg Field had been anticipated by almost two billion years.

The history of the natural reactor is an extraordinary sequence of seemingly improbable events. First, uranium from an entire watershed accumulated in concentrated local deposits, including one at a place now called Oklo. Then the conditions necessary to sustain the fission chain reaction were established; these included constraints on the concentration of uranium in the ore, on the size and shape of the lode and on the amount of water and other minerals present. After the reactor had shut down, the evidence of its activity was preserved virtually undisturbed through the succeeding ages of geological activity. Finally, the discovery of the reactor involved an investigative tour de force worthy of the best sleuths in detective fiction.

The first clue was found by H. Bouzigues, who is on the staff of the nuclear-fuel-processing plant at Pierrelatte in France. In May, 1972, he obtained a curious result during a routine analysis of a standard sample prepared at Pierrelatte from uranium ore. Natural uranium consists mainly of the isotope of atomic mass 238; only .7202 percent of the atoms are the easily fissionable isotope of mass 235. In the freshly prepared standard Bouzigues found the proportion of U-235 to be even smaller than the usual value: it was .7171 percent.

Bouzigues's analysis was performed by mass spectrometry, in which molecules are ionized and accelerated, then deflected by a magnetic field. The mass of the molecule is revealed by the extent to which it is deflected. The technique is a delicate and precise one, and when it is applied to the gaseous feed materials employed in the enrichment of uranium, it can achieve even greater accuracy than is usual under most other circumstances. The discrepancy Bouzigues had found was a small one, but it was considered significant. The French Commissariat à l'Énergie Atomique (C.E.A.) began an investigation to discover its cause.

The raw material for the isotopic analysis was not the uranium ore itself but uranium hexafluoride gas, the form in which uranium is processed for enrichment. One plausible explanation was that the gas had become contaminated with "tailings," the waste product of the enrichment cycle. The peculiar isotopic composition persisted, however, in the results of repeated analyses of other samples. The possibility of contamination was excluded from further consideration when the anomaly was traced back through the various stages in the manufacture of the uranium hexafluoride gas: through a processing plant in France to the Mounana mill near Franceville in southeastern Gabon. The ore had come from the nearby Oklo mine, operated by the Compagnie des Mines d'Uranium de Franceville (C.O.M.U.F.). Samples had been preserved from each batch of ore processed at the Mounana mill; they showed that shipments of uranium slightly depleted in U-235 had begun in 1970 and were still continuing. By mid-1972 the affected shipments from the Oklo mine involved ore that yielded about 700 tons of uranium; the deficiency of U-235 amounted to roughly 200 kilograms.

The ore body at Oklo had been defined by drilling sample cores on a closely spaced grid. Some of the cores were stored in France, and it was possible to analyze portions of them individually. Several were found to be strongly depleted in U-235. One core, removed from a region of the ore body that was then being mined, contained only .44 percent U-235.

The isotopic composition of uranium is thought to be a constant of the solar system in any one era. (It has been measured not only for many terrestrial ores but also for moon rocks and meteorites.) Chemical processes can make one region rich in uranium and leave another region poor; that is how the deposit at Oklo was formed. U-235 and U-238, however, are virtually indistinguishable chemically, so that any process that affects one of them must affect the other in the same way. Indeed, the difficulty of separating the isotopes is attested to by the size and complexity of uranium-enrichment plants such as those at Pierrelatte and at Oak Ridge, Tenn. There seemed to be no plausible mechanism in nature that might selectively remove one isotope to the extent observed in the depleted ore.

As the investigation continued, the possibility emerged that the missing U-235 had not been displaced but had simply been destroyed in situ. When the required tests were made, the explanation was suddenly obvious. Elements that are characteristic products of nuclear fission were abundant in the depleted vein, but they were almost absent elsewhere in the ore body. Their isotopic composition was quite unlike that of the natural elements, and it corresponded to the composition expected from fission. Three months after the investigation had begun in earnest the mystery was solved. Nature, not man, had constructed the world's first nuclear-fission reactor. Eventually six reactor zones were identified in the Oklo pit, four of them in strata that had not yet been mined.

The fissioning of a U-235 nucleus begins when it absorbs a neutron. The absorption of the neutron excites the nucleus and changes its shape so that about 85 percent of the time it becomes unstable and splits into two fragments and typically two or three neutrons. If at least one of the neutrons is absorbed by another fissionable nucleus and leads to fission, the reaction is

**OPEN-PIT URANIUM MINE at Oklo in the Gabon Republic contains scattered pockets of ore that in Precambrian times achieved all the conditions necessary for a fission chain reaction. Six of these "reactor zones" have been identified; part of one, designated Reactor Zone 2, is visible at the left, at the base of the nearer wall of the pit, opposite a stack of core samples draped with a blue tarpaulin. The benches and rostrum, decorated with palm fronds, were set up on the floor of the pit mine for an international meeting convened a year ago to discuss scientific aspects of the reactor.**

self-sustaining. The fragments produced by fission are almost always unequal in size—a pair might have masses of 99 and 133—and they are themselves unstable, or in other words radioactive. They decay with half-lives ranging from a few seconds to many years and yield a varied spectrum of daughter fission products. The final products include numerous stable isotopes of more than 30 elements.

The spectrum of fission products is so distinctive that it serves as an unmistakable sign that a chain reaction has taken place. In the Oklo uranium deposit the presence of these elements is convincing and quantitative evidence that a natural reactor once operated there. Both the absolute amounts of the elements and their isotopic composition can be explained only by their origin in fission.

Remarkably, at least half of the 30-odd fission-product elements have remained immobilized in the ore. These include the rare-earth elements lanthanum, cerium, praseodymium, neodymium, europium, samarium and gadolinium and also yttrium, which is not one of the rare earths but is chemically similar to them. Most or all of the zirconium, ruthenium, rhodium, palladium, niobium and silver remains, and so does some of the molybdenum and iodine. There are even remaining traces of the inert gases krypton and xenon.

Metals with a valence of one or two have a relatively high solubility in water and are readily leached away; hence the rubidium, cesium, strontium and barium made in the reactor, and probably the cadmium, have for the most part disappeared. On the other hand, there is no appreciable deficit of zirconium 90; this isotope of zirconium is produced by the decay of strontium 90, which has a half-life of about 30 years. One can conclude that little of the strontium was transported from the vicinity of the reactor

**REACTOR ZONE 2 on the floor of the pit at Oklo is marked with pegs and strings, which define the lines along which sample cores were taken. The reactor was discovered in 1972, following the observation in a uranium-processing plant in France of an anomaly in the relative abundance of the two common isotopes of uranium, uranium 235 and uranium 238. The anomaly was traced to ores from the Oklo mine, which were found to be depleted in U-235, the more easily fissionable isotope. Cores from the reactor zones contain the uranium deficient in U-235; in addition they contain elements that are characteristic products of nuclear fission. Elsewhere in the mine uranium has a normal isotopic composition and the fission products are absent. On the rock face above Reactor Zone 2 the vein of uranium ore continues. The black regions are shale containing carbonaceous material; yellow regions are oxidized uranium formed on exposure to the atmosphere.**

in that period. Lead, a final product of uranium decay, has migrated to some extent. Other fission products are made in quantities that are small compared with the amounts present naturally, and their fate has not yet been determined.

A particularly suitable element for an analysis of fission products is neodymium. It is not an abundant element and therefore the contribution from its natural background—the amount present from sources other than fission—is small. Moreover, neodymium has seven stable isotopes, ranging in mass from 142 to 150, but only six of them are manufactured as fission products. Fission fragments with a mass of 142 do not decay to neodymium but halt in a stable region of the periodic table at cerium 142. The neodymium 142 present in the depleted Oklo ores is therefore unrelated to fission, and from its amount and the known ratios of neodymium isotopes in natural deposits the background levels of the other six isotopes can be calculated. Subtracting these amounts from the total neodymium in the deposit gives the amount of neodymium made by fission.

For a complete isotopic analysis one more correction is required. Neodymium 143 and neodymium 145 both readily absorb neutrons; they are said to have a large neutron-capture cross section. Neutrons were abundant during the operation of the reactor and as a consequence many atoms of these fission products were altered by neutron capture after their formation. On absorbing a neutron neodymium 143 is converted into neodymium 144; neodymium 145 becomes neodymium 146. This effect perturbs the isotopic ratios, and it is particularly important for the mass-143 and mass-144 pair. Its magnitude can be calculated, however, and its influence can be fully accounted for. When these corrections for natural background level and for neutron capture are made, the abundance ratios of the neodymium isotopes correspond precisely to those measured experimentally in modern reactors of the appropriate type.

Similar analyses can be made of other elements present in the ore. An example is thorium. For every six atoms of U-235 that fission when they absorb a neutron, one simply captures the neutron and becomes an atom of U-236. This nucleus has a half-life of about 24 million years and decays by the emission of an alpha particle (a helium nucleus). When an alpha particle is emitted, the atomic mass of the nucleus is decreased by four and the atomic number is decreased by two. All the U-236 made in the natural reactor has by now decayed into thorium 232, a nearly stable isotope. Thorium is found in the reactor zones and is almost absent elsewhere. Similarly, U-238 in the reactor gives rise to a small quantity of U-237; this decays by a series of alpha-particle emissions to bismuth. At Oklo bismuth is present in quantity only in the reactor zones.

What conditions had to be met to achieve a nuclear reaction in the Oklo deposit? The list of requirements is hardly trivial. The basic requirement is that the flux of neutrons be sustained. On the average, the fissioning of a U-235 nucleus results in the prompt emission of 2.5 neutrons; one of them must be absorbed and must induce fission in another nucleus. The rest can be absorbed elsewhere or escape.

A chain reaction is possible in unenriched uranium containing .72 percent U-235 but only under rather special circumstances. A quantity of deuterium (the isotope of hydrogen with an atomic mass of two) must be present to serve as a "moderator." This is the system employed in the Canadian natural-uranium ("Candu") power reactors. Alternatively, the reactor could be constructed in a geometric lattice of uranium and a moderator with carefully specified dimensions. Neither a deuterium moderator nor a precisely assembled lattice is likely to be found in nature. About the best configuration that has a reasonable probability of being formed accidentally is a mass of relatively pure uranium oxide whose size is large compared with the distance a neutron travels before it is captured. This distance and hence the required size of the deposit are minimized by the presence of an effective moderator. It is reasonable to expect that such a moderator would be present in the form of water saturating the ore.

Given these best plausible conditions, no natural reactor could operate today with uranium containing .72 percent of the mass-235 isotope. The ratio of U-235 to U-238, however, has not been constant throughout the history of the earth. The half-life of U-235 is about 700 million years, that of U-238 about 4.5 billion years. Since the fissionable isotope is decaying faster, it must have been more abundant in the past. Indeed, from the decay rates it is possible to extrapolate into the past to determine the relative abundance of the two isotopes at any time back to the formation of the solar system. When the earth formed, natural uranium was about 17 percent U-235; the isotope has reached its present abundance of .72 percent through an exponential decline. The minimum abundance for the operation of a plausible natural reactor is 1 percent, which means such a reactor could have operated up until about 400 million years ago. In the much older Oklo deposit the relative abundance of U-235 was about 3 percent.

Apart from the isotopic ratio the concentration of uranium in the ore also affects the rate of the reaction; for a chain reaction it must average at least 10 percent. There are also constraints on the shape of the ore body. A sphere is the most efficient shape and requires the smallest quantity of uranium, but it is sufficient that the ore be deposited in seams at least half a meter thick. In a thinner deposit too many neutrons would escape. The reactor zones in the Oklo mine meet the requirements of uranium concentration and seam thickness.

An important requirement for the operation of the reactor is that the neutrons emitted by the fissioning nuclei be slowed down; this is the function of the moderator. The neutrons are emitted with high energy and therefore high velocity; in that state they are readily absorbed by U-238. Ideally the neutrons should be slowed to a "thermal" distribution of energies: their velocities should be those characteristic of random thermal motion at the temperature of the medium. This can be accomplished if each neutron collides with a great many nonabsorptive nuclei. Slow or thermal neutrons are much less likely to be absorbed by U-238, and hence they are more likely to survive to encounter a nucleus of U-235.

By far the best moderator available in a natural reactor is water. The moderation is provided primarily by the hydrogen atoms in the water, and for an ore that is two billion years old the optimum ratio is about 6 percent water by weight. The water of crystallization in a sedimentary ore such as that at Oklo should more than satisfy this requirement. In addition, at Oklo the medium was probably saturated with groundwater, which would have overmoderated the neutrons. If the ore became chain-reacting in this condition, the heat evolved would evaporate some of the water, so that optimum moderation would eventually be attained. For this reason the constraints on the amount of water initially present are not confining.

Finally, the reactor could not operate in the presence of large quantities of elements that strongly absorb neutrons (that is, elements that have a large neutron-capture cross section). Such elements are called neutron "poisons"; among the more potent ones are lithium, boron and many of the rare earths. There is no evidence that excessive amounts of such poisons were present in the ore before the reaction began.

These circumstances varied during the course of the reaction, changing its rate and eventually stopping it entirely. They are responsible for controlling the power generated, both over short periods and over the entire history of the reactor. Together they functioned to limit the reactor to modest power levels.

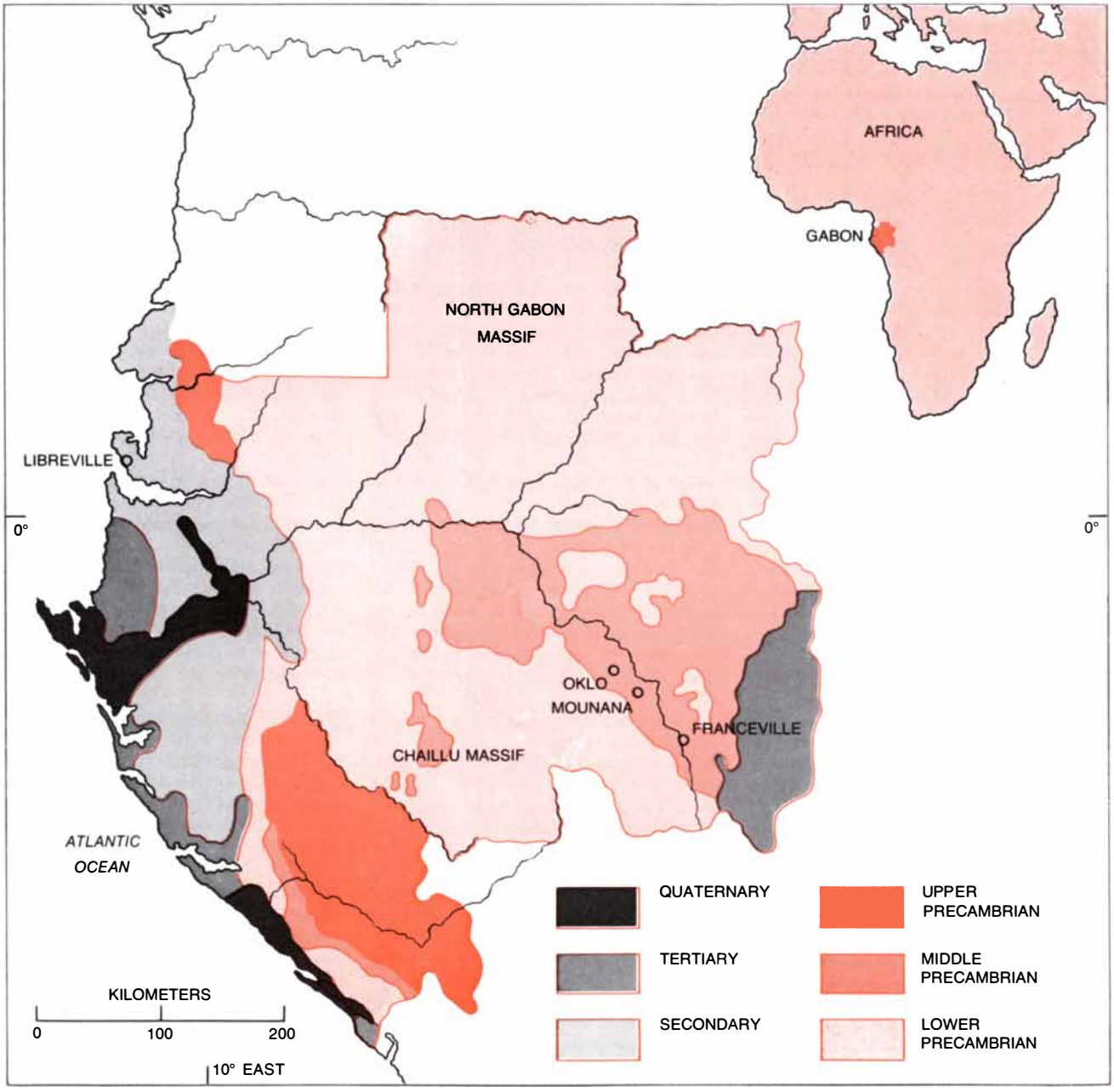
In the long run the behavior of the Oklo reactor was determined by the continuous decrease in the relative abundance of U-235. Almost all this decrease was a direct consequence of the fission itself—the reactor was consuming its fuel—and it was therefore proportional to the total flux of neutrons in the reactor. As I have mentioned, the conversion of neodymium 143 to neodymium 144 (by neutron capture) is also proportional to the total neutron exposure in the ore, and the present isotopic ratios of neodymium therefore predict the total depletion in U-235. This calculation gives a result about 40 percent greater than the observed depletion; in other words, knowing the amount of U-235 present initially and the amount remaining, we find that the amount consumed was greater than the difference. Several factors could contribute to this discrepancy, including changes in the concentration or shape of the

deposit during the reaction, and the accretion of ore afterward. The principal cause, however, is an additional nuclear reaction. As we have seen, U-238 readily captures high-energy neutrons; it is thereby converted to U-239. This nucleus decays by the emission of a beta particle (an electron). In beta decay atomic mass remains essentially unchanged but atomic number increases by one. Hence U-239 becomes neptunium 239. Through a second beta emission the neptunium becomes plutonium 239, which decays by alpha emission with a half-life of 24,400 years. The product of the last decay is U-235. Thus the absorption of fast neutrons by U-238 results in the eventual creation of additional U-235.

The operation of the reactor might also have been modified by a decrease in the quantity of neutron poisons present. As soon as a nucleus captures a neutron it is transformed, usually into a nucleus with a smaller neutron-capture cross section. In this way neutron poisons may have been "burned out" of the ore soon after the reactor began operating. If the initial amounts of elements such as lithium and boron were large enough, this effect could have been a major factor controlling the reactor.

Short-term control of the reaction was almost certainly dominated by the amount of water present. If the stratum containing the reactor was buried deep enough, the boiling point of the water may have been 300 degrees Celsius or higher. When the reactor reached that temperature, the water boiled away until the ratio of hydrogen to uranium reached a critical value where the reactor was undermoderated. The power generated by the reactor then leveled off and remained roughly constant, at a level just sufficient to compensate for the heat transferred to regions outside the reactor. (It is possible that the ore deposit was buried so deep that the pressure was great enough to prevent water from boiling, but that has not been demonstrated.)

The possibility of a sustained nuclear reaction in a natural uranium ore deposit was first considered more than 20 years ago. In 1953 George W. Wetherill of the University



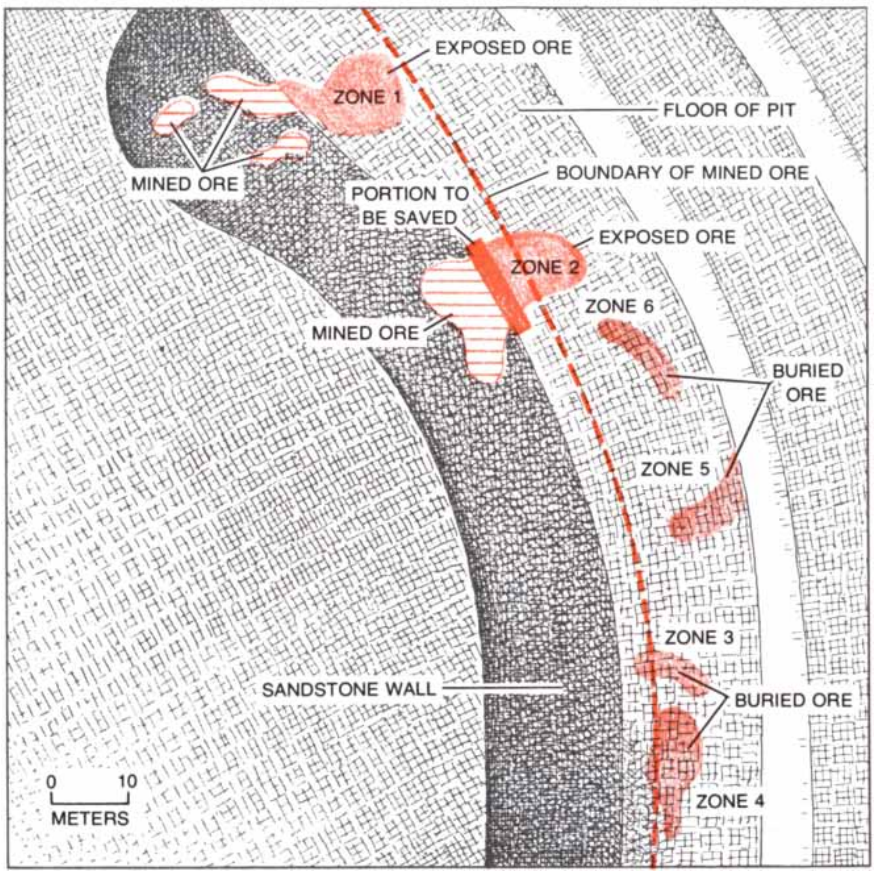

**GEOLOGY of the region surrounding the Oklo mine is predominantly Precambrian, that is, older than about 600 million years. The mine itself is at the edge of a basin made up of sedimentary rock from the Middle Precambrian period; it borders an expanse of igneous rock from the Lower (earlier) Precambrian. The analysis of cores from the reactor zones suggests that the fission chain reaction began between 1.7 and 1.9 billion years ago. Independent evidence gives approximately the same age for the strata in which the reactor is embedded.**

of California at Los Angeles and Mark G. Inghram of the University of Chicago stated with reference to a pitchblende deposit: "[Our] calculation shows that 10 percent of the neutrons produced are absorbed to produce fission. Thus the deposit is 25 percent of the way to becoming a pile [a reactor]. It is also interesting to extrapolate back 2,000 million years, when the uranium 235 abundance was [3 percent] instead of .7. Certainly such a deposit would be closer to being an operating pile." Three years later Paul K. Kuroda of the University of Arkansas described the requirements for a natural reactor in a terrestrial uranium deposit in more detail. His description of an "unstable" ore mass comes very close to describing the conditions at Oklo. In spite of such speculations the announcement of the Oklo reactor was received by American nuclear scientists with skepticism. Some of the world's best physicists had constructed the Stagg Field reactor with careful attention to mechanical detail, to the purity of the materials and to the geometry of the assembly. Could nature have achieved the same result so casually?

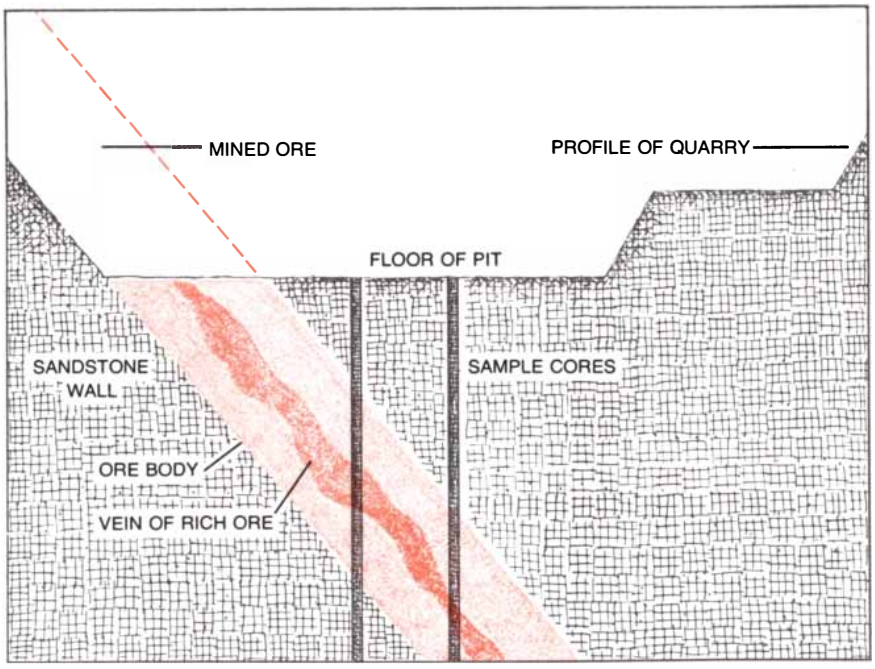
We now know that the answer is yes. Remember again the importance of the difference in date. In the two billion years between Oklo and Stagg Field the relative abundance of U-235 declined from 3 percent to .7 percent. A Precambrian physicist would have found it almost easy to build a nuclear reactor. In retrospect it seems inevitable that it happened accidentally.

Last June 70 investigators from 20 countries met in Libreville, the capital of Gabon, to discuss the "Oklo phenomenon." The meeting was sponsored by the International Atomic Energy Agency (IAEA), the French C.E.A. and the government of Gabon. Its business was to present and review analyses of the Oklo ores, carried out largely in French laboratories but also in the U.S., Britain, the U.S.S.R. and Australia.

The meeting opened with a spectacular expedition: a flight over the tropical rain forest to Franceville in southeastern Gabon and from there some kilometers by car to the floor of the open-pit mine at Oklo. From a rostrum decorated with palm fronds representatives of the sponsoring organizations and ministers of the Gabonese government welcomed us. We sat on benches at the edge of Reactor Zone 2, which was marked out by pegs and strings defining the sampling lines. J. P. Pfiffelmann, chief geologist of the C.O.M.U.F., took up a position at the edge of the reactor zone and lectured on the geology of the formations surrounding us. Behind him a sandstone wall slanted up at an angle of 45 degrees; there were ripple marks on its face attesting to its aquatic origin. The exposed reactor zone, about a meter wide and 10 meters long, extended along the floor of the pit near the sandstone wall. Immediately beyond the reactor zone rose a bench of unmined ore, displaying a continuation of the uranium vein. Water and atmospheric oxygen had converted traces of black, reduced uranium to a slurry of uranium oxide, which formed bright yellow




**SIX REACTOR ZONES at Oklo were found in lenses of exceptionally rich ore. Parts of zones 1 and 2 had already been mined when the reactor was discovered, and their boundaries are therefore conjectural. Zones 3, 4, 5 and 6 have not yet been exposed; they lie below the present floor of the pit and were found by drilling cores. A portion of Zone 2 has been pinned to the rock face so that it will not be destroyed when the pit is deepened. In ore from the reactor zones the average concentration of uranium is from 20 to 30 percent, more than 50 times the concentration elsewhere. On the other hand, the uranium in the reactor zones is strongly depleted in U-235.**

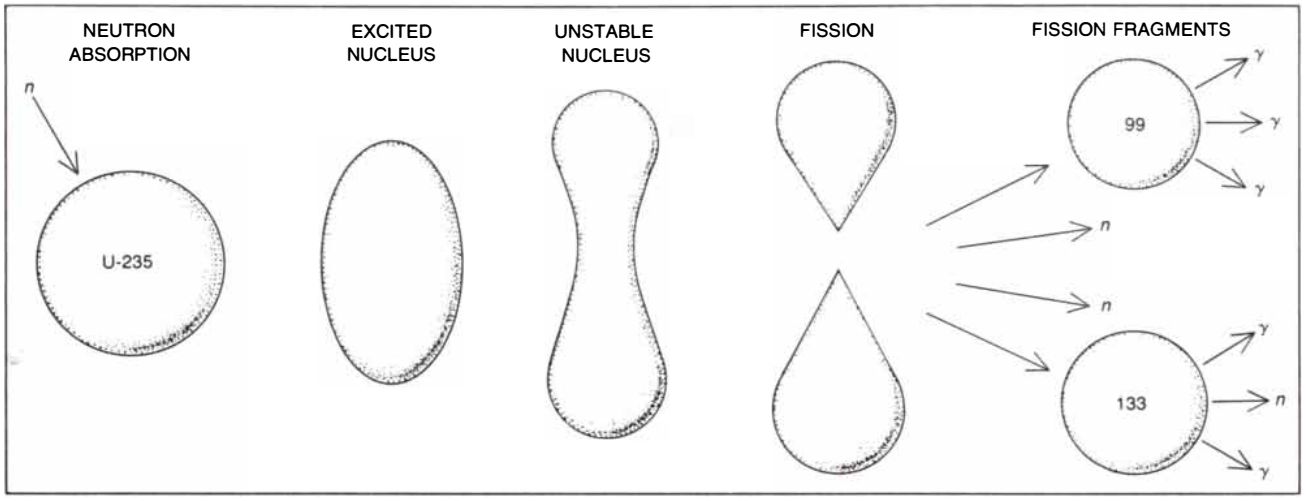



**ORE BODY AT OKLO, shown in a schematic profile of the mine, lies above a sandstone wall with an average slope of about 45 degrees. The reactor zones are within the rich vein of ore, which is roughly a meter thick. The zones generally have a lenticular cross section. The extent of the ore body and the location of the reactor zones were revealed by removing core samples.**

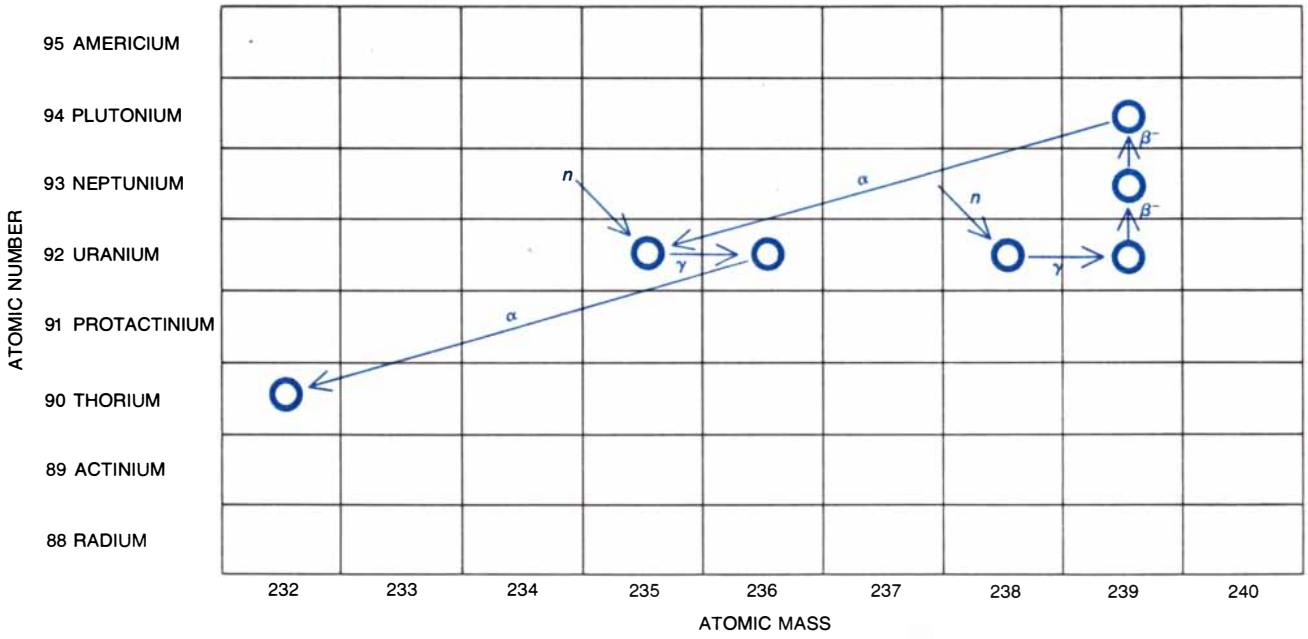
plaques on the buff-colored ore of sandstone and clay.

The landscape around us had once been a river delta. On an ancient African watershed crystalline igneous rocks were eroded by running streams, releasing minute quantities of heavy metals and their oxides. The heavier material accumulated in bottom sediments and pebble conglomerates, much like the placer deposits of gold and other noble metals found in streams today.

About two billion years ago the chemistry of the waters changed abruptly. The change was brought about primarily by the rise of blue-green algae, the first organisms capable of photosynthesis. As a result of their activity the oxygen content of the waters rose, and in some regions it became high enough to convert reduced uranium into more soluble oxidized compounds. The uranium was once again mobilized, and it remained in solution until it reached the river delta. There the bottom sediments were rich in organic ooze and oxygen-poor




**FISSION OF A NUCLEUS of U-235 is induced by the absorption of a thermal, or slow, neutron ($n$), which excites the nucleus and deforms it. About 85 percent of the time the deformed nucleus becomes unstable and splits into two fragments of unequal size. The fission fragments shown have atomic mass numbers of 99 and 133; many other pairs of fragments are possible and each has a well-defined probability. The fragments are themselves unstable and are transformed by their subsequent decay, so that the total spectrum of fission products includes many isotopes of more than 30 elements. At the moment of fission high-energy photons, or gamma rays ($\gamma$), are emitted, as are a few neutrons. For a chain reaction to be sustained at least one neutron must be absorbed and must induce fission in another U-235 nucleus.**




**TRANSFORMATIONS OF HEAVY NUCLEI affect the rate and the nature of the fission chain reaction. Most U-235 nuclei that absorb a slow neutron become unstable and fission, but about 15 percent dissipate their energy of excitation by emitting gamma rays and simply retain the neutron. The addition of a neutron does not change the atomic number or the chemical identity of a nucleus, but it increases the atomic mass by one, so that the U-235 becomes U-236. This nucleus is unstable and decays by the emission of an alpha particle ($\alpha$): a helium nucleus, made up of two protons and two neutrons. In alpha emission atomic number decreases by two and atomic mass decreases by four, so that U-236 becomes thorium 232. U-238 readily captures neutrons, particularly if they have a somewhat higher energy than thermal neutrons. It is thereby transformed to U-239, a short-lived species that decays by the emission of a beta particle ($\beta^-$): an electron. Beta decay can be considered as the conversion of a neutron into a proton; it does not alter atomic mass, but it increases atomic number by one. The U-239 thus decays quickly into neptunium 239, which in turn decays by a second beta emission into plutonium 239. The plutonium decays, with a half-life of 24,400 years, by alpha emission to yield U-235. Plutonium is readily fissionable, but in the Oklo deposits the rate of the chain reaction was low enough so that most of the plutonium decayed to U-235 before it could absorb a neutron and fission.**

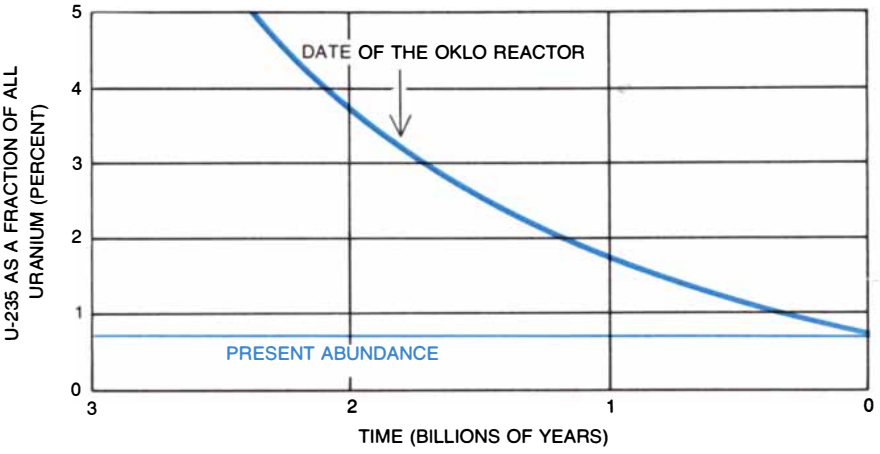
conditions again prevailed. The oxidized uranium was converted into the reduced form and compacted into the sandstone ore that now surrounded us. Subsequently the basement granite sank and the sedimentary layer deepened; then the granite to the west was uplifted, and it tilted the sedimentary overburden to its present angle. The ore layer, which averaged .5 percent uranium by weight, was fractured and water circulated through the new channels, creating pockets of rich ore that in places became almost pure uranium oxide. It was in these rich pockets that fission chain reactions began as soon as a critical mass of uranium had accumulated.

If uranium dissolves so readily in oxygenated water, how has the Oklo deposit survived almost two billion years? The sedimentary basin was apparently buried deep enough to protect the uranium ore from redissolution during most of its history. Only recently (within the past few million years) has the ore horizon approached the surface, where normal prospecting procedures could succeed in identifying it. Thus the series of special circumstances necessary to the discovery of the Oklo phenomenon includes not only those processes that led to the formation of a natural critical mass of uranium but also the unusual geophysical and geochemical conditions that preserved the ore body for almost half the lifetime of the planet and finally brought it to the surface.

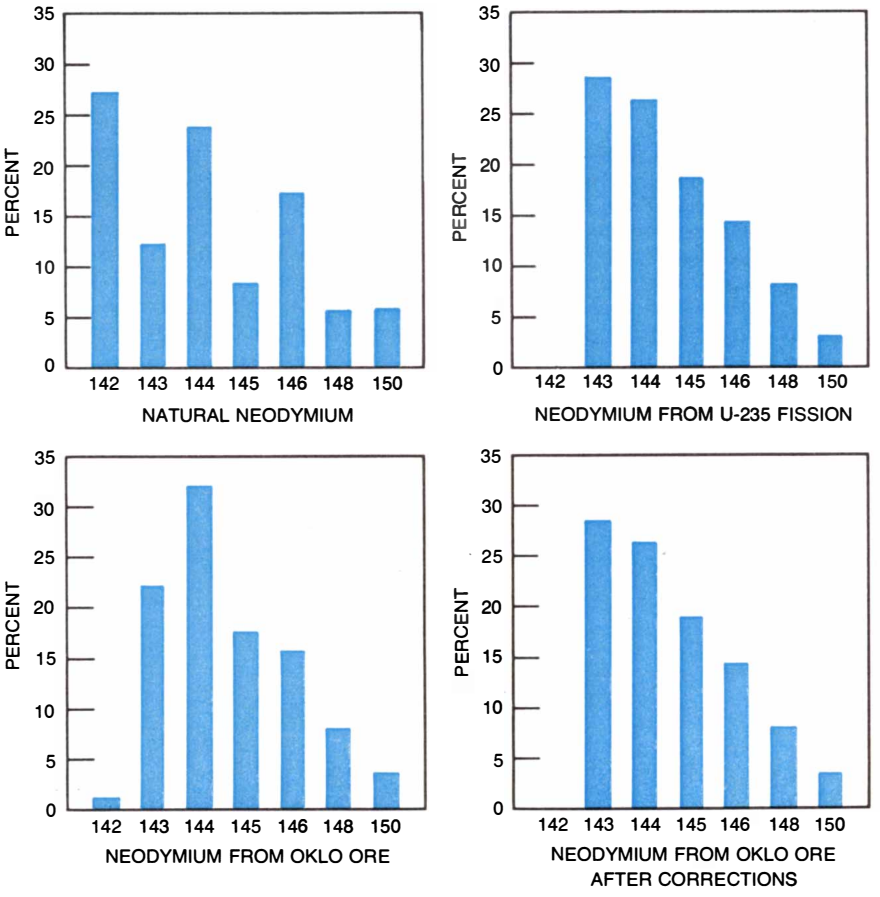
Back in Libreville, Roger Naudet, the director of the C.E.A.'s study of the Oklo phenomenon, reported some of that group's findings. They have estimated that the total energy released in the reactor zones was 15,000 megawatt-years, representing the consumption of six tons of U-235. That is approximately the energy produced by the reactor in a large nuclear power plant in four years.

Only about two-thirds of the fission events involved the U-235 that was originally present. Most of the remainder were in additional U-235 created by neutron capture in U-238 and the subsequent decay through plutonium 239. A few percent of the events were fissions of U-238 induced by fast neutrons, and another few percent were attributed to plutonium 239 that fissioned before it decayed. The modest contribution from plutonium 239 indicates that the reaction lasted much longer than the 24,400-year half-life of that isotope. The duration was on the order of hundreds of thousands of years.

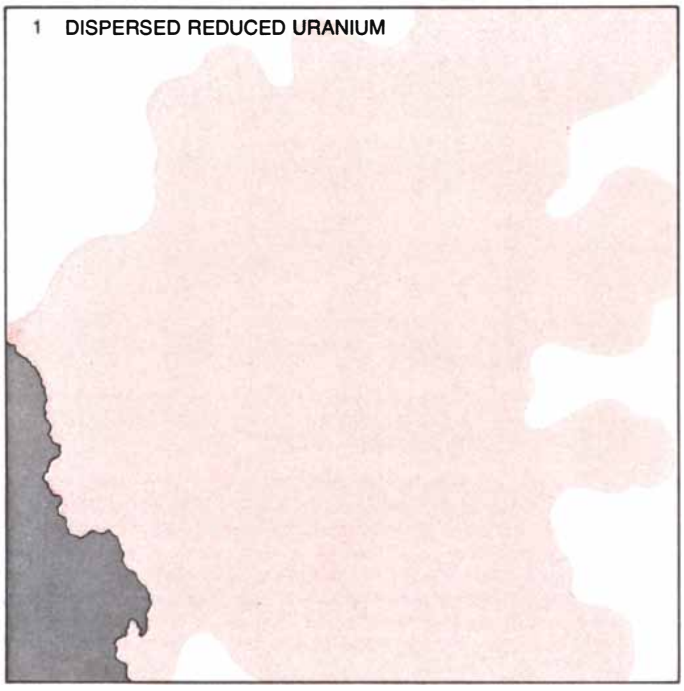
The same conclusion can be deduced from studies of heat transfer in the reactor. Since the reactor could not continue to operate if the temperature much exceeded the boiling point of water, the power level was probably limited to a few tens of kilowatts. This calculation is somewhat uncertain because it is not known how much water was actually flowing through channels in the ore body, but even if the power level was as high as 100 kilowatts, the duration of the reaction would still be 150,000 years. The total

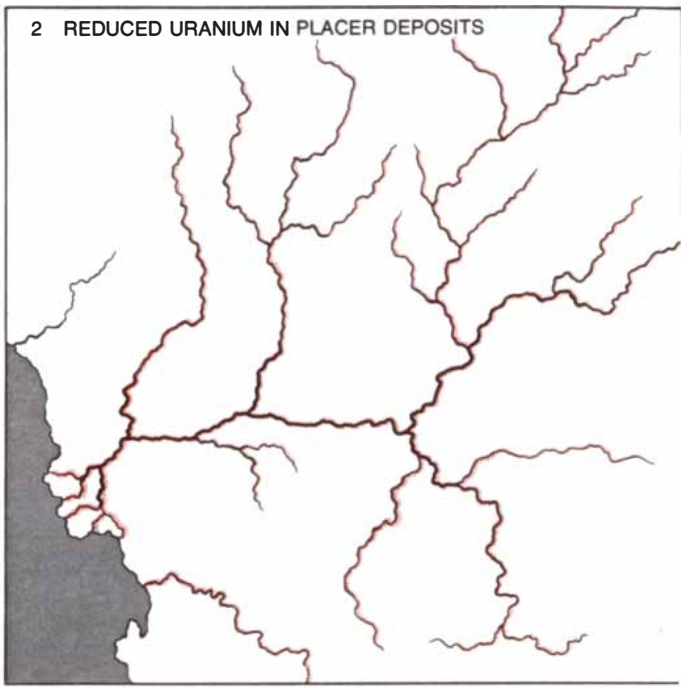



**ISOTOPIC COMPOSITION of uranium has changed during the history of the earth. Because U-235 decays about six times faster than U-238 the abundance of U-235 as a percentage of all uranium has declined. It is thought that when the earth formed some 4.6 billion years ago, uranium was about 25 percent U-235; today a commonly accepted value for the relative abundance of U-235 is .7202 percent. When the Oklo reactor was operating, the uranium in the ore contained about 3 percent U-235. The rate of radioactive decay is constant, and at any one moment the isotopic composition of uranium should be essentially the same everywhere in the solar system; it was for this reason the anomalous isotope ratios in ores from Oklo were investigated.**




**ISOTOPIC ANALYSIS of neodymium, a fission product, provides convincing evidence for a chain reaction at Oklo. Natural neodymium has seven stable isotopes, ranging in mass from 142 to 150, and their relative abundances are a characteristic of the element. Neodymium made by the fission of U-235 has a distinctively different composition; in particular, the isotope of mass 142 is entirely absent. At first the isotopic composition of neodymium from the Oklo reactor zones resembles neither of these distributions, but its origin becomes apparent when two corrections have been made. First, there is a little natural neodymium in the ore, and this must be subtracted. Second, neodymium 143 readily captures neutrons and is thereby converted into neodymium 144; similarly, but to a lesser extent, neodymium 145 is converted into neodymium 146. Since neutrons were abundant in the reactor, the ratios of these isotopes were substantially altered. When the presence of the natural element and neutron capture are taken into account, the composition of the neodymium in the Oklo ores closely matches that produced by fission.**

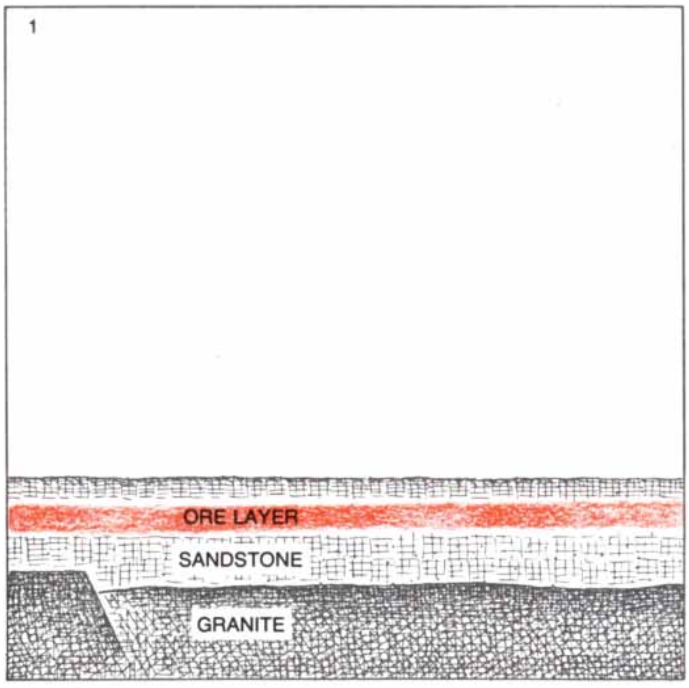


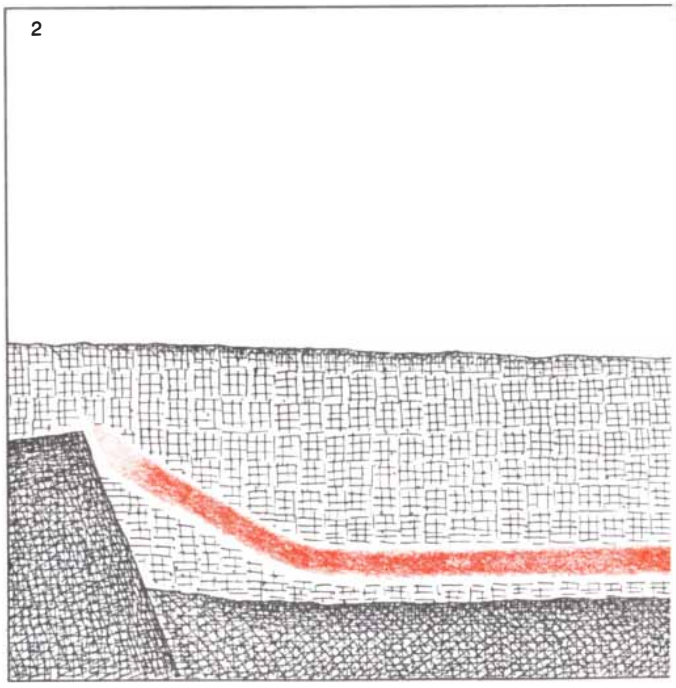




**ACCRETION OF THE ORE DEPOSIT at Oklo involved the concentration of uranium derived from an entire watershed. The uranium (*color*) was originally dispersed in igneous rocks over a large area (*1*). As the rocks were eroded by weathering, the uranium accumulated in streambeds in a relatively reduced state (*2*). It may have formed placer deposits like those in which gold and low-grade, Precambrian uranium ores are found today. Some two billion years ago a biological development profoundly altered the disposition of the uranium:**

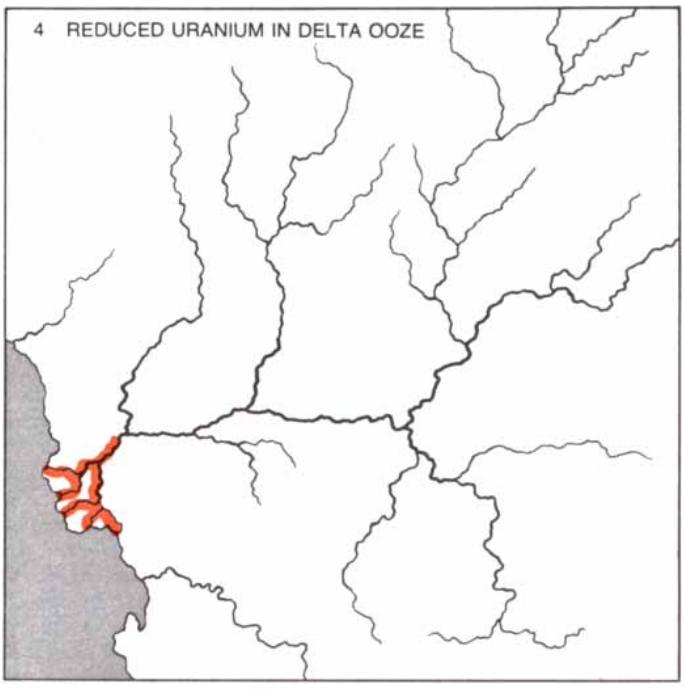
time elapsed from the initiation of the chain reaction to the final shutdown was probably even greater, because the reactor did not necessarily operate continuously.

The unusual stability of the ore deposit was confirmed by analysis of samples taken every 2.5 centimeters along several cross sections of the reactor zones. On this scale there was generally good correspondence between the extent of U-235 depletion and the total neutron flux over the life of the reactor, as calculated from isotopic ratios in neodymium. Although some puzzling anomalies were found at the borders, there was little migration of uranium inside the zones. Distinct excursions in both the neutron flux and the U-235 depletion were observed in the vicinity of faults in the ore body. When the reactor was functioning, these faults were most likely water-filled channels that trapped neutrons and increased their local density. Such neutron traps are a feature of some modern research reactors.



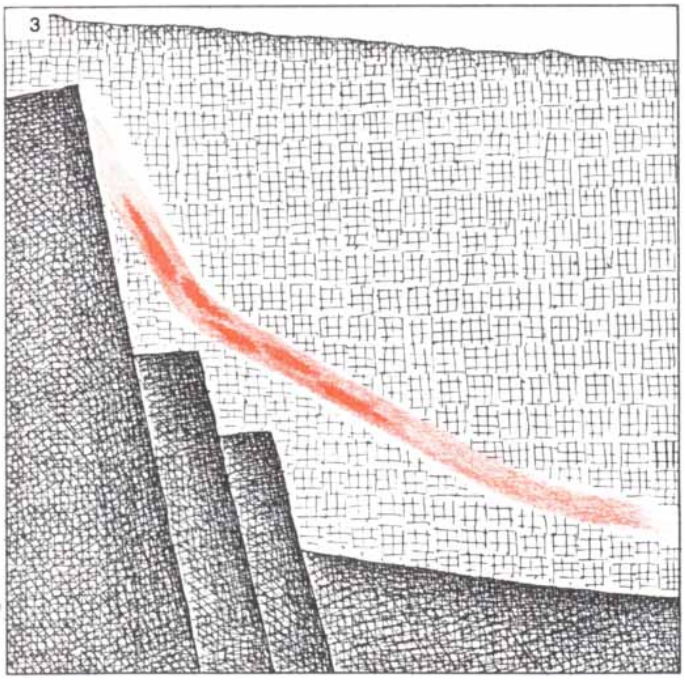

**GEOLOGICAL TRANSFORMATION of the ore body created the conditions necessary for the operation of the natural reactor and preserved the evidence of the reaction for almost half the life of the planet. After the ore had been deposited in the river delta it was compacted along with other sediments into a layer of sandstone (*1*) overlying basement rock of granite. Gradually the sedimentary overburden deepened and the ore layer sank (*2*), while the granite to the west of the deposit began to be uplifted. As the uplift continued, the vein of ore**

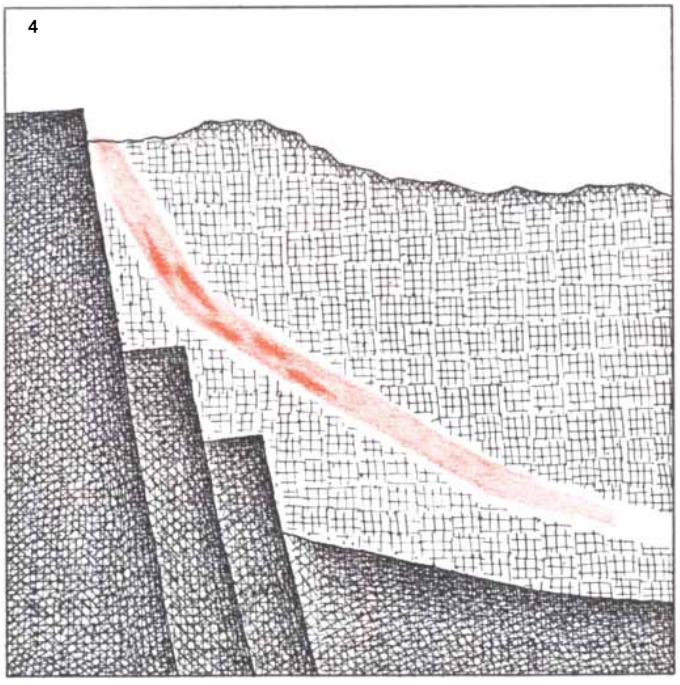




**the proliferation of photosynthetic algae increased the concentration of oxygen in the water. Highly oxidized uranium is more soluble than the reduced form, and the uranium was therefore dissolved and carried downstream (*3*). It remained in solution until it reached the delta of the river system, where sediments rich in organic ooze again created a condition of oxygen deficiency. In these sediments the uranium was returned to the reduced form and was precipitated out of the solution (*4*). In the delta the ore was covered by later sediments.**

A group of investigators from the University of Paris employed an ion probe to study the distribution of isotopes within individual grains of ore. The partitioning of several fission products between grains of uraninite and clay was noted, but the rare earths and uranium were found in the same grains. More remarkable was the complete confinement of U-235 and U-238 to the same grains. Almost half of the residual U-235 in the reactor zones is a daughter product of plutonium 239. The fact that no regions were enriched in this daughter product indicates that the precursor plutonium was completely immobilized for times comparable to its half-life of 24,400 years. The possible relevance of this observation to proposals for the long-term storage of nuclear wastes was pointed out by investigators from both France and the U.S.

Finally, both French and American participants presented estimates of the age of the reactor based on analyses of the ore samples. The estimates assume that the




**was tilted to its present average slope of about 45 degrees. The tilting caused numerous fractures, so that water could percolate through the ore, creating small pockets of very concentrated ore (*3*). In these pockets the chain reaction began as soon as enough uranium had accumulated. For most of its history the ore was probably buried deep under other sedimentary rock, where it was protected from dissolution and dispersal by groundwater. Only much later, in the past few million years, did it approach the surface where it could be detected (*4*).**

abundance of uranium and neodymium in the ores has not been extensively altered since the reactor stopped functioning. The absolute abundances of those elements and their isotopic compositions then give a date for the initiation of the reaction. The best fit to the American data is an age of from 1.7 to 1.9 billion years, which is in good agreement with independent estimates of the age of the host geological formation.

Outside the conference, discussion was given over to freewheeling speculation. Did prokaryotes (living cells without nuclei) evolve into eukaryotes (cells with nuclei) as early as 1.8 billion years ago? Was it possible that Africa was not only the cradle of man but also the birthplace of the cells that led to all the higher forms of life? There was general agreement that the plot should be worked into a science-fiction story but that without considerable embellishment the motion-picture rights would be worthless. It would have been far better to introduce a spaceship from another planet that had dumped its used reactors at the site, replenished its fuel supply and departed.

For the three years from the discovery of the depleted uranium to the symposium in Libreville, the C.O.M.U.F. had suspended mining of the very rich ores in the reactor zones. Now it was time to deepen the pit and mine the uranium in the protected regions. Presumably the highly depleted ores would be processed separately. It was proposed to save a portion of Reactor Zone 2 by walling it off and pinning it to the 45-degree sandstone face. The ore will be suspended above the new floor of the pit, an elevated monument to the first discovery of a natural fission reactor.

Clearly it would be interesting to know if there have been other natural reactors of the Oklo type. The final stage of the process that formed the Oklo lode could have been a very common one in Precambrian times: as the oxygen content of the atmosphere rose, reduced uranium in scattered deposits would have become mobile, and it could then have been reconcentrated in richer ore deposits wherever a reducing environment was encountered. Rich uranium ore deposits have been found in other geological formations of approximately the same age, not only in Africa but also in other parts of the world, particularly in Canada and northern Australia. None of these deposits has yet been identified as a reactor site. It is entirely possible that chain-reacting ore lodes formed in these areas and have since disappeared. They may have been buried under younger sediments, where they are unlikely to be discovered, or they may have been dispersed as a result of geophysical instabilities or geochemical mobility.

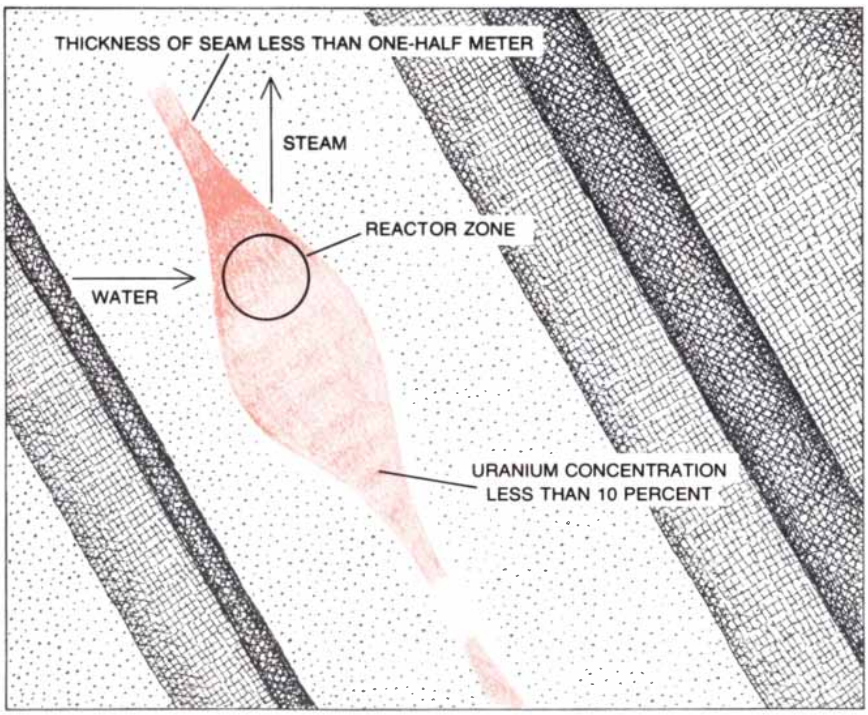
What is the probability of such dispersion? Apart from its obvious scientific interest, the answer to this question has possible economic and technological consequences. It has a direct bearing on the problem of the long-term storage of nuclear wastes. In this regard the stability of the Oklo deposit is plainly encouraging. It contains all the chemical elements of interest and demonstrates that, at least in this one environment, they remained in place for an enormously long time.

At the Libreville symposium Ray D. Walton, Jr., of the U.S. Energy Research and Development Administration (ERDA) presented the results of a preliminary American attempt to determine the significance of the Oklo phenomenon for radioactive-waste storage. He suggested that at the time of the reaction the principal radioactive products that were released into the environment in measurable amounts were krypton 85 and possibly cesium 137 and some strontium 90. Plutonium, the most worrisome reactor product, was efficiently confined.

The adsorptive properties of shales and clays and the extreme stability of many elements bound in such matrixes were known before the discovery of Oklo, and suggestions for the storage of reactor products in such formations have been under investigation for many years. It is obviously difficult to devise an experiment that would evaluate the stability of an adsorbed metal ion for a million years or more under field conditions. Since Oklo resembles such an experiment, the data have been examined with great care to determine what part of them might be relevant to the problem of waste storage.

The possibility that other ore deposits once supported chain reactions also affects the producers and buyers of uranium. It should be of interest as well to those regulatory agencies whose responsibility it is to account for all fissionable materials; they are expected to notice mysterious shortages of a few hundred kilograms of U-235.

In this regard it is interesting to note that not all natural reactors would necessarily give rise to depleted ores. As the isotopic abundance of U-235 diminished over geologic time, the conditions necessary for reactor operation became more restrictive, but at the same time the nature of the chain reaction was subtly altered. In particular, the relative importance of neutron capture in U-238 increased, since that isotope came to form a progressively larger fraction of the total uranium. If a natural reactor was able to form as late as 800 million years ago, when the relative abundance of U-235 was about 1 percent, it might actually have become a breeder reactor. The U-235 consumed in the reaction would have been more than replaced by new U-235 created by the decay of plutonium. The pitchblende deposits in the former Belgian Congo were




**RATE OF A CHAIN REACTION is determined by the flux of neutrons, and at Oklo this was influenced by several factors acting in combination. The reaction could begin only in regions of the ore body where the concentration of uranium was greater than about 10 percent. The shape of the deposit was also important: thin seams allow too many neutrons to escape. Elements that act as neutron "poisons," strongly absorbing neutrons, can also prevent a reactor from functioning, but apparently none of these elements was abundant at Oklo when the chain reaction began. A final requirement is a moderator, a substance that slows neutrons so that they are not too readily captured by U-238. At Oklo the moderator was water, and the amount present was presumably the most important factor, over relatively brief periods, controlling the power level of the reactor. Any increase in power would raise the temperature and boil off water, slowing the reaction. Through this mechanism power output was maintained at a modest level. In the long term the reaction was controlled and finally stopped by the diminishing abundance of U-235.**

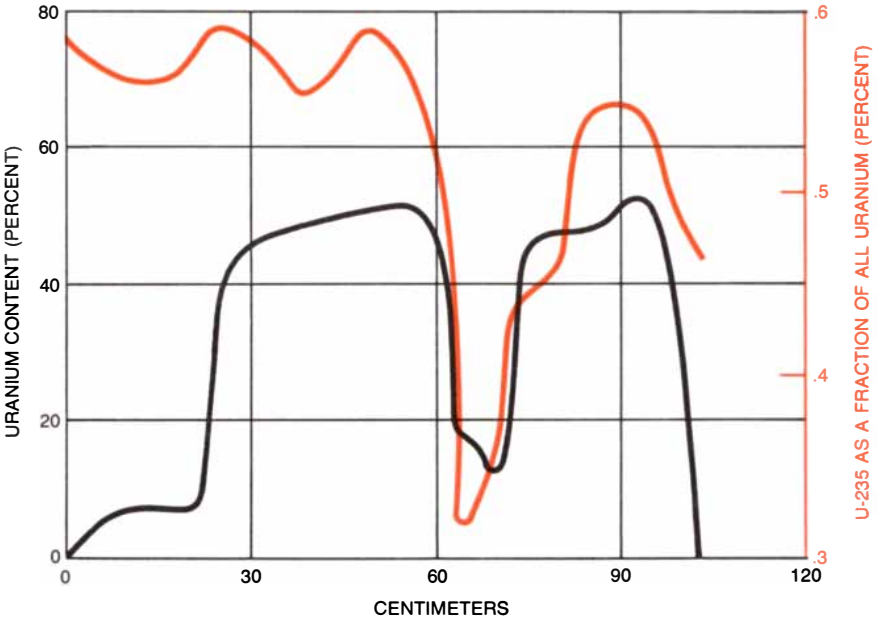
of the appropriate age. They have now been mined out, but precise isotopic analyses are available for a few samples of the ore. It is provocative that these samples appear to be slightly enriched in U-235.

The number of economically significant deposits of any mineral is determined by the difference between the rate at which the deposits form and the rate at which they are dispersed. The second term in this equation—the one dealing with rates of dispersion—has largely been overlooked. Its importance to waste storage is apparent. Ultimately it may also determine the probability of discovering other natural reactors.

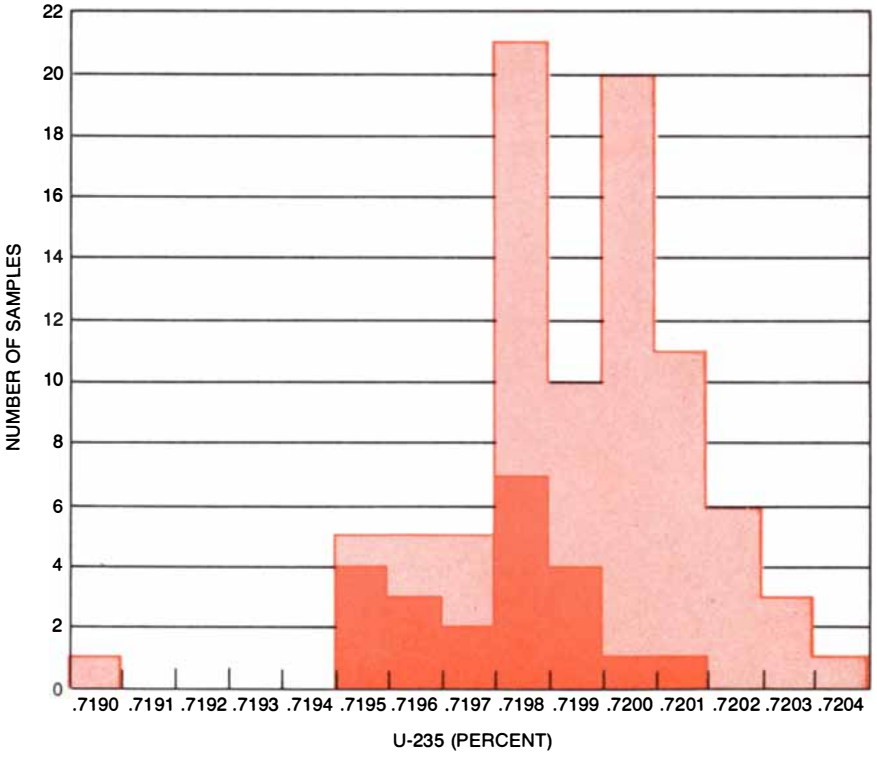
The statement that the isotopic composition of uranium is constant throughout the solar system is based mainly on analyses accurate to about .1 percent. At that level of precision the ratio is indeed constant. The more refined mass spectrometry possible at uranium-enrichment plants gives results accurate to about .01 percent, and at this level variations in the ratio have been discovered. In particular, sedimentary deposits from the Colorado Plateau in the U.S. are depleted in U-235 by about .03 percent. These variations have generally been attributed to chemical differentiation of the isotopes in sandstone rocks. Another hypothesis is possible: the depletion might result from the operation of a reactor of the Oklo type in the Colorado Plateau, the remains of which have since been dispersed throughout the region. The total uranium reserves of the plateau are on the order of 400,000 tons; to explain the observed depletion requires a reactor that caused a net loss of five tons of U-235. We do not yet have enough information to decide which of these explanations is the more likely to be correct.

If dispersion was not the general fate of natural reactors, we can hope to find their dormant remains by surveying rich uranium deposits more than a billion years old. In principle it would even be possible to recognize a reactor zone in which most of the uranium had been dissolved and washed away, since the less mobile rare earths would probably remain in place. Any ore pocket containing rare earths, yttrium, zirconium, niobium, ruthenium and rhodium, all in abundances greater than .01 percent, could be considered a candidate. The origin of these elements in a fission reaction could be demonstrated by isotopic analysis.

On balance, the prospects for finding additional reactors seem good. If Oklo had been a unique event in the history of the earth, the probability of our having discovered it must approach zero. Considering the almost accidental way its existence was revealed, one is tempted to conclude that similar reactors have already been mined out without being noticed. In time we shall learn whether to regard the survival of the Oklo deposit as a unique phenomenon in natural history or as a particularly valuable experiment in long-term geological storage. In any case one message is already clear. In the design of fission reactors man was not an innovator but an unwitting imitator of nature.




**STABILITY OF THE OKLO DEPOSIT during the 1.8 billion years since the reactor operated is suggested by a detailed examination of the ores. In some regions samples were analyzed every 2.5 centimeters. (The horizontal axis gives distance along the sampling line.) Generally the concentration of uranium in the ore was closely correlated with the depletion in U-235, as at the extreme left. The sharp dip in uranium concentration is caused by a crack in the ore sample. When the reactor was operating, the crack was apparently filled with water and served as a "neutron trap" that slowed neutrons and greatly increased the efficiency of the reaction in its vicinity. That increased efficiency is reflected in the corresponding decline in the abundance of U-235. The correlation of the two curves suggests there has been little migration of uranium.**




**ABUNDANCE OF U-235 in 88 samples of uranium ore shows a clearly bimodal distribution. The peak at .7200 percent represents ores mined mainly in Canada, Europe and Australia. The peak at .7198 percent is produced by ores taken from the Colorado Plateau region of the U.S. One group of these ores, mined in New Mexico, is shown separately (*dark color*); it plainly suggests that uranium from the Colorado Plateau has a U-235 content smaller than the world average. One possible explanation of this small discrepancy is that the isotopes were separated by some chemical process in the ore-bearing rocks. Another explanation is that a natural reactor once operated in the region and that its depleted ore has been dispersed throughout the plateau.**

# Interactions between Hormones and Nerve Tissue

*Steroid hormones secreted by the gonads and the adrenal cortex can be traced to target cells in the brain. In the newborn animal the sex hormones help to lay down brain circuits that control later behavior*

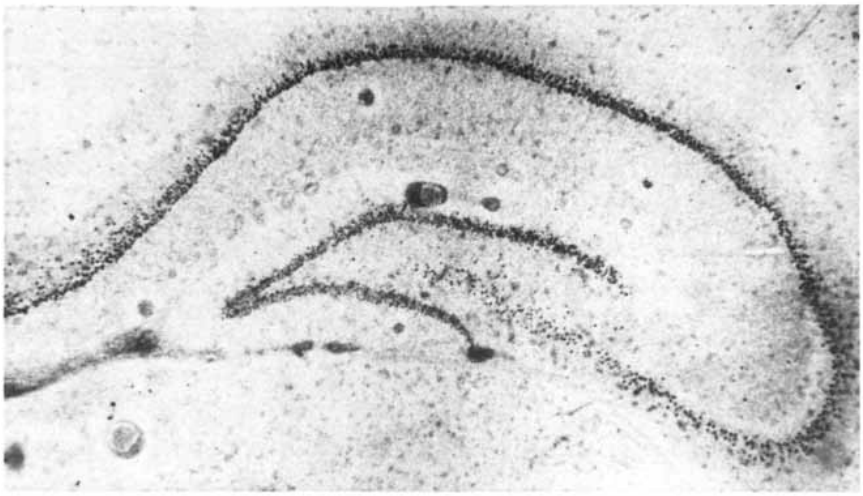
by Bruce S. McEwen

The steroid hormones that are secreted by the cortex of the adrenal glands and by the gonads are potent substances. Throughout the body the adrenocortical hormones help to regulate the utilization of energy and the balance of electrolytes, such as sodium and potassium; they also affect mood by acting on certain areas of the brain. The gonadal steroids, secreted by the ovaries and the testes, act more specifically on tissues associated with sexual functions: in females the vagina, the uterus, the oviducts and the breasts, and in males the seminal vesicles and the prostate. The sex hormones also stimulate sexual behavior by acting on nerve cells in the brain.

Great progress has been made in identifying the target regions of such hormones in the brain. It has been established that the sex hormones directly influence sexual differentiation of the brain, that is, the pattern of nerve connections and hence the organization of nerve circuits in specific parts of the brain during embryonic and early postnatal development. The resulting neuronal pattern is thereafter not susceptible to permanent hormonal modification. Rather, in the adult animal the role of the sex hormones is limited to influencing the circuits' functional efficiency. Paradoxically the hormone that elicits the male brain pattern in newborn rats seems to be estradiol, one of the estrogens, or female hormones. Although the hormone that reaches the brain of the newborn male rat is testosterone, secreted in the testes, the male hormone is converted into estradiol by enzymes in the nerve cells that are the targets of sexual differentiation.

The first experiment to suggest that gonadal steroids directly affect brain function was reported in 1849 by Arnold A. Berthold of the University of Göttingen. Berthold found that roosters that had been castrated no longer crowed, fought or exhibited sexual behavior. He also found that if he transplanted testes into the abdominal cavity of the castrated roosters, the characteristic masculine behavior reappeared. Because the transplanted testes did not develop connections with the rooster's nervous system but did develop connections with its circulatory system, Berthold deduced that the behavioral signals dispatched by the testes reached the brain through the blood and not through the nerves.

We now know that in higher vertebrates the adult brain contains distinct populations of cells that are sensitive to different steroid hormones, some to estradiol and testosterone, which are secreted by the gonads, and some to the steroid hormones of the adrenal cortex. In our laboratory at Rockefeller University we have located various hormone-sensitive brain cells and have undertaken to establish how they fit into the nerve pathways that govern behavior and regulate the hormone-producing glands. Here I shall discuss our findings and also describe how the steroid products of the testes participate in the sexual differentiation of the developing brain.



**STEROID-HORMONE RECEPTORS IN RAT BRAIN can be located by administering a steroid labeled with tritium, the radioactive isotope of hydrogen. In this case the steroid was corticosterone, one of the principal hormones secreted by the adrenal cortex. One or two hours after administration of the labeled steroid frozen sections of the animal's brain are placed in contact with photographic emulsion and stored for several months. The decaying tritium atoms make black dots in the emulsion and reveal the presence of cells containing receptors for corticosterone. This low-power magnification of an autoradiogram of the hippocampus, which is a primitive region of the rat's brain, shows that nerve cells in the region are heavily labeled.**

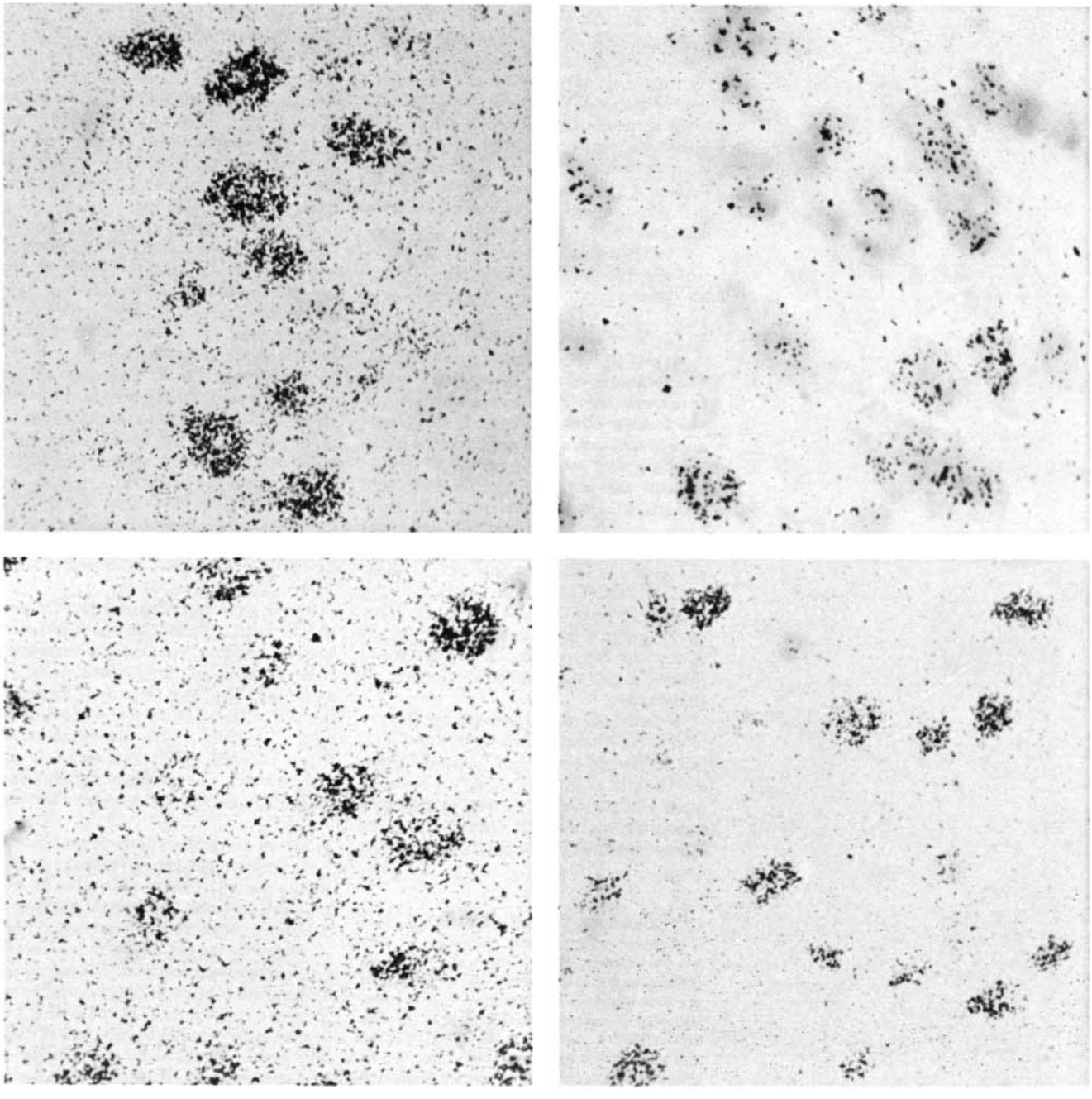
Berthold's deduction that testicular hormones directly affect brain function was verified in 1969 by Ronald J. Barfield of Rutgers University, who restored sexual activity in castrated roosters by implanting tiny amounts of testosterone in the preoptic area of the brain. Barfield's work on the rooster was a continuation and extension of other work that showed the direct neural effects of gonadal steroids not necessarily related to sex behavior. In 1957 Bela Flerkó and János Szentágothai of the Medical University of Pécs in Hungary reported that when small fragments of ovarian tissue are implanted in the hypothalamic region of the brain of female rats, the rats' ovaries atrophy. In the early 1960's Robert D. Lisk of Princeton University reported similar results with hypothalamic implants of tiny amounts of the ovarian hormone estradiol. Both Lisk and Richard P. Michael of Emory University found that in female rats

and cats such implants could also restore the sexual receptivity that had been lost after removal of the ovaries.

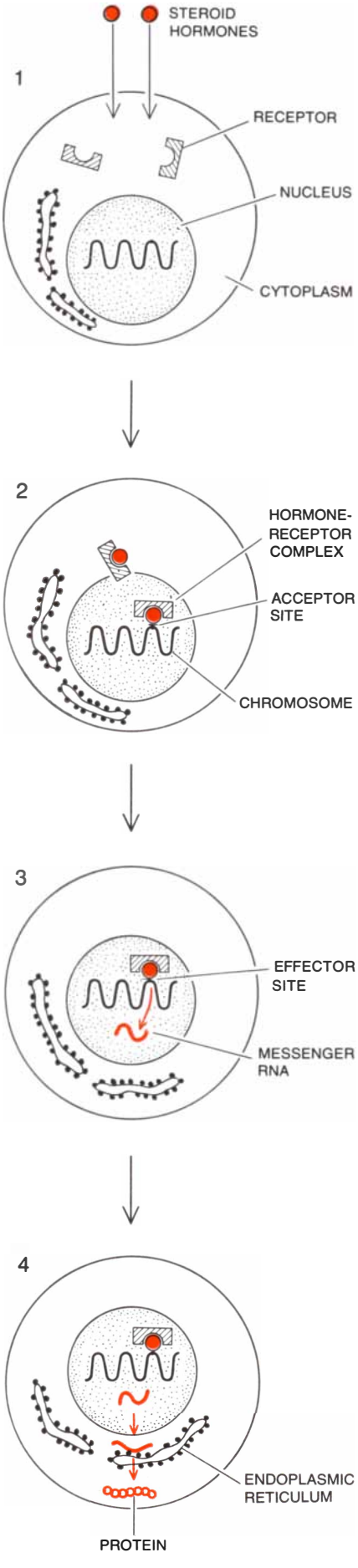
One can demonstrate that steroid hormones gain access to the brain from the blood by injecting radioactively labeled steroid hormones into the circulation and measuring the amount of radioactivity that appears in the brain tissue. Not only the brain but also virtually all the other tissues of the body are accessible to the circulating steroid hormones. Certain cells, the target cells, accumulate and retain the hormone by means of specific intracellular receptor proteins, which are believed to reside in the cytoplasm of the target cell. The hormone-protein complex is able to enter the cell nucleus and interact with the genes. The steroid hormone, coupled to its receptor protein, causes portions of the genetic material, DNA, to become accessible to the enzymes and substrates that can form new messenger-RNA molecules along one of the strands of DNA.

The messenger-RNA molecules bear the information necessary to direct the formation of new protein molecules in the cytoplasm of the cell. The new protein molecules enable the target cell to carry out its functional response to the hormone. Thus the oviduct of the hen responds to estradiol by manufacturing the protein ovalbumin, which is secreted into developing eggs. The uterus of female mammals responds to estradiol by synthesizing a great variety of cell proteins that enable its cells to grow, divide and prepare for the implantation of the fertilized ova [see "The Receptors of Steroid Hormones," by Bert W. O'Malley and William T. Schrader; SCIENTIFIC AMERICAN, February].

It is reasonable to assume that steroid



**BRAINS OF RAT AND RHESUS MONKEY are compared in these** autoradiograms for their ability to accumulate tritium-labeled estradiol, a major sex hormone, in nerve cells of the hypothalamus (*panels at top*) and tritium-labeled corticosterone, one of the adrenocortical hormones, in nerve cells of the hippocampus (*panels at bottom*). The two photomicrographs at the left represent the brain of a rat; the two at the right represent the brain of a rhesus monkey. In each case the most heavily labeled regions are the nuclei of the nerve cells, indicating that these are the ultimate target of the two kinds of steroid hormone. Autoradiograms, which were made by John L. Gerlach in the author's laboratory at Rockefeller University (corticosterone) and by Donald W. Pfaff (estradiol), are enlarged some 1,600 diameters.




hormones affect the genetic material by similar molecular mechanisms in all target cells, wherever in the body they may be. Hence the brain, the most complicated organ of the body, should be amenable to the same kinds of biochemical investigation as those successfully pursued with the oviduct and the uterus. The principal limitations of such studies are the low concentration of hormone-sensitive cells in the brain and the large number of hormones capable of influencing brain function. Fortunately for the experimenter, cells sensitive to particular steroid hormones are commonly found in clusters in certain brain regions. The high density of the sensitive cells in such regions makes it possible to conduct the same kinds of biochemical investigation that can be conducted with more homogeneous tissues. By combining information on the localization of hormone-sensitive cells within the brain with information gathered from implanting hormones in specific brain regions, from electrical recordings of nerve-cell activity and from the administration of drugs that alter the electrical activity of the brain a picture can be formed of the circuits of nerve cells that may be involved in the control of particular hormone-sensitive behavior patterns.

Hormone-sensitive neurons are present only in certain distinct brain regions. The technique of autoradiography enables us to make these hormone-sensitive neurons visible under the microscope. In this procedure ovariectomized rats are injected intravenously with estradiol labeled with tritium, the radioactive isotope of hydrogen, and are killed one or two hours later. Their brains are removed, frozen and sectioned. The sections are then placed in contact with photographic emulsion and stored for three to 12 months. The radiation emitted by the decaying tritium atoms reveals quite precisely where the estradiol was deposited within the cell nucleus, even though the nucleus is only about five or 10 micrometers in diameter.

With the aid of autoradiography Donald W. Pfaff of Rockefeller University and Walter E. Stumpf of the University of North Carolina have found that in the brain of adult rats the highest density of estrogen-concentrating cells is in the preoptic area, the hypothalamus and an adjacent area, the amygdala. These are all areas of the "primitive" brain, the archipallium, which has long been known to play a role in sexual behavior. Tiny implants of purified estradiol in two of these regions (the preoptic area and the hypothalamus) facilitate female sexual behavior and cause atrophy of the ovaries. Because the function of the amygdala in reproductive physiology is not well understood, a role cannot be assigned to the estrogen receptors in that area.

Estradiol appears to be bound to receptors in the cell nuclei of neurons. In 1970 Richard E. Zigmond in my laboratory found large amounts of tritium-labeled estradiol in cell nuclei isolated from the brain tissue of ovariectomized female rats to whom the steroid had been given an hour or two before they were killed. Other investigators, examining the cytoplasm of brain cells, have found estrogen-receptor sites, indicating the presence of molecules that can carry the hormone into the cell nucleus. Thus estrogen target cells in the brain conform to the general model of steroid target cells elsewhere in the body.

When it is loaded to full capacity with tritiated estradiol, each cell nucleus isolated from the preoptic area, the hypothalamus and the amygdala contains 3,000 to 5,000 molecules of hormone. Each cell nucleus isolated from the nearby pituitary gland, another important estrogen target, contains on the average 12,000 molecules of hormone. The receptor capacity of cell nuclei in the uterus is similar to that of cell nuclei in the pituitary. In the pituitary 80 percent of the cells are labeled, whereas in the samples of the preoptic area, the hypothalamus and the amygdala fewer than 50 percent of the cells contain estrogen receptors. It appears that there are also some differences in the number of receptors in individual target cells in these various tissues.

Recent work by Pfaff and Joan I. Morrell has shown that the localization of estradiol-sensitive neurons in the brain is remarkably constant in fishes, amphibians, birds and mammals. The most important finding in the effort to relate these observations to human physiology is that the brain of the rhesus monkey, which like man is a primate, has the same pattern of estradiol-concentrating neurons as the brain of the rat.

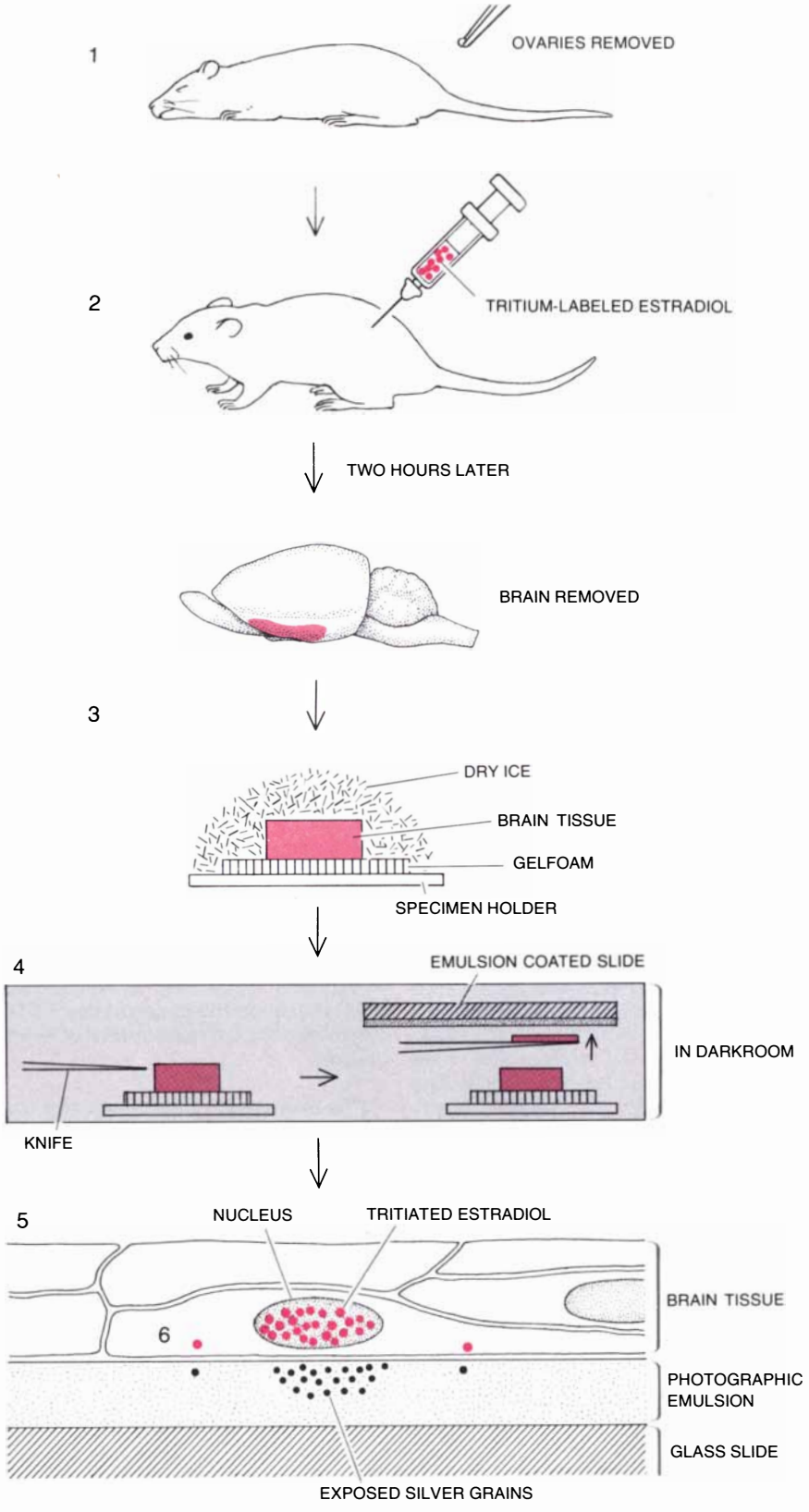
One of the major effects of estradiol on the brain of a female rat is to make the animal sexually receptive. It takes at least 20 hours, however, for a single injection of estradiol to bring about an increase in sexual receptivity in a female rat from which the ovaries have been removed. This time lag is independent of the dose of the hormone and is similar to the latency in the female rat's estrous cycle between the increase of estradiol secretion by the ovaries and the appearance of behavioral estrus. The time lag has enabled a number of laboratories to examine the intracellular events that may be involved in the effect of estradiol on sexual behavior. Administering a single behaviorally effective dose of tritium-labeled estradiol, we were able to show that receptors in

**CELLULAR RESPONSE to steroid hormones is depicted schematically. Although steroids are presumably able to enter all cells, only certain target cells contain specific receptor proteins that bind the hormone (*1*). Receptor-hormone complexes are able to pass through the membrane that surrounds the cell nucleus and attach themselves to acceptor sites on the chromosome containing the genes (DNA) of the cell (*2*). The receptor triggers the synthesis of messenger RNA corresponding to the gene at an effector site (*3*), which may or may not be different from the acceptor site. Messenger RNA leaves nucleus and migrates to endoplasmic reticulum, where it presides over the synthesis of protein encoded by gene (*4*).**

the nuclei of cells in the pituitary and in the three most heavily labeled brain regions (the hypothalamus, the preoptic area and the amygdala) are occupied for less than 12 of the 20 hours. In fact, the maximum labeling of receptor sites comes within the first two hours. Thus the estrogen does not have to be present at the time of its behavioral effect. It would therefore seem that estradiol initiates metabolic changes within the target neurons, which in turn determine the readiness for the behavioral response.

Since the cell nucleus plays a role in the action of estradiol, the metabolic changes may involve the synthesis of RNA and protein. The hypothesis can be tested by seeing if estrogen action in the brain can be blocked by substances that inhibit the synthesis. Two such inhibitors are actinomycin D, an inhibitor of RNA synthesis, and cycloheximide, an inhibitor of protein synthesis. Roger A. Gorski of the University of California School of Medicine at Los Angeles, Richard E. Whalen of the University of California at Irvine and David M. Quadagno of the University of Kansas have shown that small implants of actinomycin D and cycloheximide in the preoptic area of the rat brain reversibly block the facilitation of female sexual behavior that is normally induced by estrogen. The inhibitors are only effective, however, if they are applied within 12 hours after the estrogen. The additional time lag before the appearance of behavioral estrus has not yet been accounted for in terms of other cellular events.

Estradiol also appears to play a role in the neural regulation of sexual behavior in adult male rats. Estradiol receptors are found in male and female brains in the same regions and in similar amounts. Moreover, the male hormone testosterone is transformed in the brain into one of two hormonal steroids: dihydrotestosterone and estradiol. The transformation into estradiol, which was discovered by Frederick Naftolin of McGill University and Kenneth J. Ryan of the Harvard Medical School, is not so surprising in view of the fact that the same conversion occurs in the normal biosynthetic pathway for estradiol in the gonads. Working in my laboratory, Ivan Lieberburg has recovered tritium-labeled estradiol from the brain-cell nuclei of rats after injecting tritium-labeled testosterone into the animals. The distribution of labeled estradiol derived from testosterone is not, however, like the pattern resulting from the administration of tritium-labeled estradiol itself. Testosterone-derived estradiol was not found, for example, in the pituitary gland, where estrogen receptors are abundant, because pituitary tissue lacks the converting enzymes. Testosterone-derived estradiol was recovered from receptors in the cell nuclei of the preoptic area, the hypothalamus and the amygdala. It is not clear what function, if any, testosterone itself has in the brain of the adult male rat. One possible function of the testosterone-derived estradiol is suggested by the work of Larry Christensen and Lynwood Clemens of Michigan State University. They showed




**LOCATION OF STEROID TARGET CELLS is established by autoradiography. One begins by eliminating the animal's normal source of the steroid under investigation. Here the ovaries, the source of estradiol, are surgically removed (*1*). Estradiol labeled with tritium is injected (*2*). An hour or two later the animal's brain is removed and frozen (*3*). Sections of the brain are placed against a photographic emulsion on a microscope slide (*4*) and stored for several months. Electrons from the decaying tritium atoms expose silver atoms in the emulsion (*5*). Since the electrons travel only one or two micrometers in the emulsion, it is easy to tell by examining the developed autoradiogram what fraction of the tritiated estradiol molecules were delivered to the cell nucleus (which has a diameter of five to 10 micrometers) and what fraction of the molecules remained in the cytoplasm (*6*). The great majority of the molecules reach the nucleus.**

that estradiol implants in the preoptic area are more effective than testosterone implants in restoring the male sexual behavior of castrated male rats.

The other major neural metabolite of testosterone, dihydrotestosterone, is relatively ineffective in restoring male sexual behavior even when it is implanted directly in the brain of castrated rats. Dihydrotestosterone does, however, increase the effectiveness of estradiol in restoring male sexual behavior when both are given to castrated male rats. Thus dihydrotestosterone may have a normal role in promoting male sexual behavior. It also appears to regulate the secretion of hormones by the hypothalamus and the pituitary, which in turn stimulates sperm formation and testosterone secretion by the testes. Receptors for dihydrotestosterone have been detected in the rat's brain and pituitary. They are less plentiful than those for estradiol. Their distribution within the brain also differs from the distribution of the estrogen receptors in that they are more plentiful in the septum and the hypothalamus than in other brain regions. Dihydrotestosterone receptors in the brain and the pituitary resemble those found in the prostate gland and the seminal vesicles, where dihydrotestosterone stimulates the growth and the secretory activity of those organs.

The second principal source of steroid hormones in man and other vertebrates is the adrenal cortex. The influence of adrenal steroids on the brain is not as well understood as the influence of estradiol and other sex hormones. Nevertheless, there are indications that adrenal steroids do significantly affect brain function. In human beings changes in mood are brought about by either an excess or an insufficiency of adrenal-steroid secretion. Such changes have been reported as a side effect of adrenal-steroid treatment of inflammation of the skin or the joints. Adrenal steroids have also been administered to regulate the ability of patients to detect sensory stimuli. Robert I. Henkin and his colleagues at the National Heart and Lung Institute find that people with Addison's disease (adrenal-steroid insufficiency) are more sensitive to sensory stimuli, such as sound and taste, than healthy people. On the other hand, they are less accurate than normal people in identifying the nature of the stimulus, for example in recognizing words or in distinguishing sweet solutions from sour ones. Both of these defects are corrected by therapy with adrenal steroids.

When the adrenal steroid corticosterone is labeled with tritium and injected into rats or monkeys from which the adrenals have been removed, the steroid turns up predominantly in two regions of the brain: the hippocampus and the septum, which also belong to the primitive brain. Steroid-receptor sites are found in both the cytoplasm and the nuclei of nerve cells in these two regions, indicating that corticosterone functions inside brain cells in the same way that other steroids do.

A potential role for adrenal steroids in the hippocampus can be inferred from experiments showing that the administration of adrenal steroids to human volunteers depresses the rapid eye movement (REM) that characterizes certain states of sleep. REM sleep seems to be associated with dreaming. In experimental animals the hippocampus shows a characteristic electrical activity, the theta rhythm, during REM sleep. It is therefore possible that corticosterone alters the characteristics of hippocampal nerve cells so that they become less sensitive to the neural stimuli that evoke the theta rhythm.

Not all adrenal steroids interact to the same degree with the same brain receptor sites. For example, tritium-labeled dexamethasone, a synthetic steroid, is selectively concentrated by the pituitary gland and becomes attached to receptor sites in the nuclei of pituitary cells. Although corticosterone also binds to such sites, dexamethasone binds much more readily, according to experiments conducted by my colleague Ronald de Kloet. (On the other hand, dexamethasone binds less effectively than corticosterone to receptor sites in the hippocampus.)

The output of steroids from the adrenal cortex is regulated by the amount of adrenocorticotrophic hormone (ACTH) secreted by the pituitary. It appears that through a feedback loop the production of ACTH in turn is regulated by the number of pituitary-cell receptor sites occupied by adrenocortical steroids. Patients whose adrenal cortex is overactive are frequently treated with adrenal steroids in an effort to reduce the pituitary's output of ACTH. The finding that pituitary receptor sites respond more strongly to dexamethasone than to corticosterone may explain why the synthetic steroid is more effective in suppressing ACTH output and thus in treating adrenal hyperfunction.

The neurons that respond to steroid hormones are part of complex circuits of nerve cells that connect stimuli from the senses with specific effectors of responses. To illustrate, let us return to the example of estradiol and reproduction in female rats. In the normal estrous cycle of the rat the pituitary secretes large amounts of luteinizing hormone (the "LH surge") in the afternoon of proestrus, approximately 30 hours after the initial increase in estradiol secretion by the ovaries. The LH surge causes ovulation to occur about 12 hours later. The LH surge does not take place if the ovaries are removed before the increase in estradiol secretion. If ovariectomized rats are given estradiol, however, the LH surge comes once again at the appropriate time.

The pituitary secretes some LH when estradiol has not been administered, but the amount is insufficient to cause ovulation. Although the effect of estradiol is to facilitate the secretion of LH, estradiol is not the true stimulus that initiates the LH surge. The stimulus for LH secretion arises from a biological clock in the brain, which is set to a specific 24-hour rhythm by the relative amounts of light and darkness detected by the eyes. The effector for LH secretion is a group of neurons that secrete a hormone consisting of 10 amino acid units from nerve endings in the base of the hypothalamus into the capillaries of the portal circulatory system of the hypothalamus and the pituitary. This short system of capillaries carries the hormone, called luteinizing hormone–releasing hormone (LH-RH), to the pituitary, where it stimulates the appropriate cells, the gonadotrophs, to release LH. The LH travels in the general circulation to the ovaries, where it induces the rupture of mature ovarian follicles, thereby releasing ova into the reproductive tract. Estradiol facilitates this sequence of events not only by increasing the amount of LH-RH secreted but also by elevating the sensitivity of the pituitary cells to release LH in response to LH-RH.

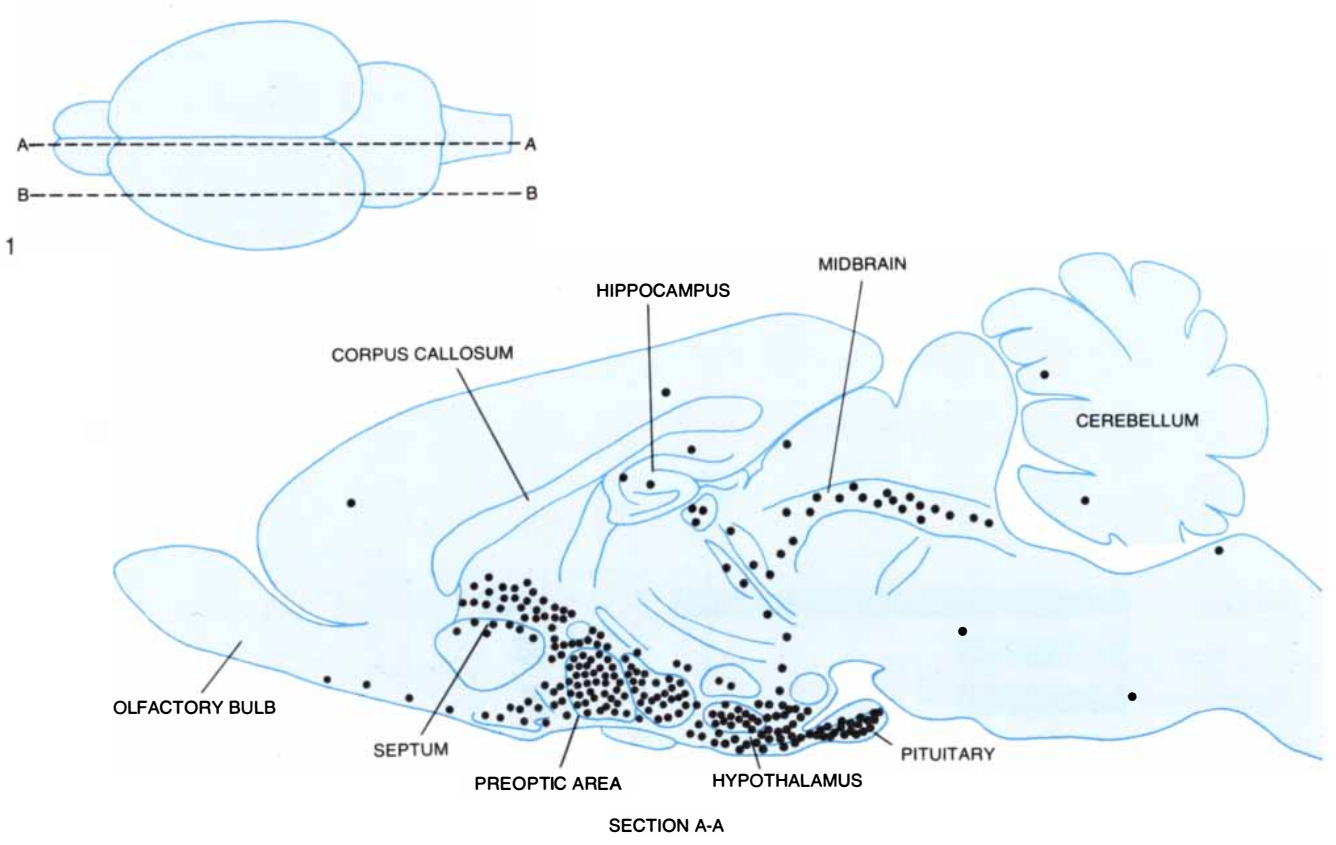
In the normal estrous cycle of rats the females exhibit their sexual behavior pattern every four days on the evening preceding ovulation. They exhibit it about 36 hours after the rise in estradiol secretion by the ovaries. If the ovaries are removed several days before testing females for sexual behavior, however, the female's response to the male is either to run away or to fight off the male's advances. If estradiol is given to ovariectomized female rats to replace the missing ovarian secretion, sensory stimuli, such as the male rat's grasping the female's flanks, cause her to assume the mating posture. The posture is called the lordosis response, from the Greek for "bending backward." Both the rump and the head of the female are raised and held rigid, making the back concave. The effector system in the brain for the lordosis response is a circuit of neurons that connects the sensory inputs from the flanks, the back and the pelvis with muscles in the back and the limbs. The incoming sensory information passes up the spinal cord and into the network of estradiol-sensitive neurons in the brain, which acts as a kind of switching mechanism that sends a return flow of information down another set of neurons in the spinal cord, causing the appropriate muscles to contract.

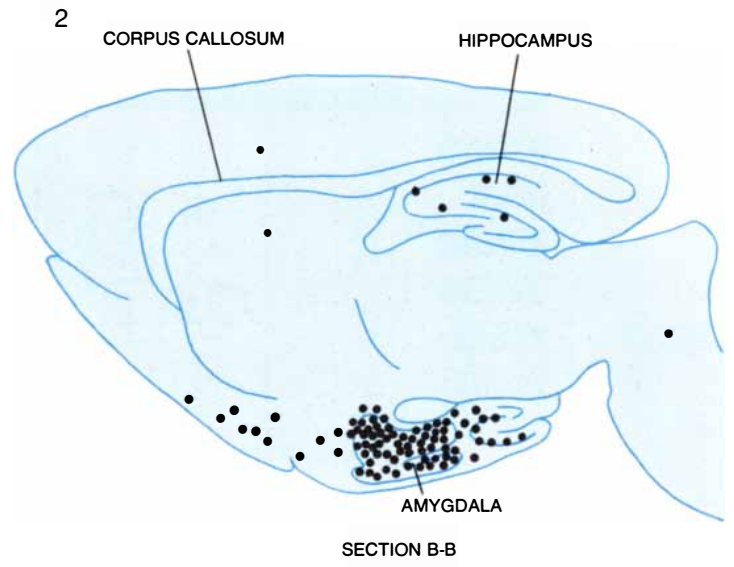
Neurons, including those that mediate the lordosis response, communicate with one another by means of specific chemical neurotransmitters, such as acetylcholine, norepinephrine and serotonin. The transmitters are released from synaptic endings and alter the electrical activity of adjacent neurons by way of specific receptor sites on their surfaces. At some of the receptor sites the transmitter is excitatory and increases the electrical activity of the responding neuron; at other sites the transmitter is inhibitory and decreases the activity. Therefore depending on which neurons are activated by specific stimuli, the outputs controlling the muscle contractions are either activated or inhibited. The action of estradiol in such neural networks may be to modify the capacity of some steroid-sensitive neurons for releasing their specific neurotransmitter and of others for responding to the trans-

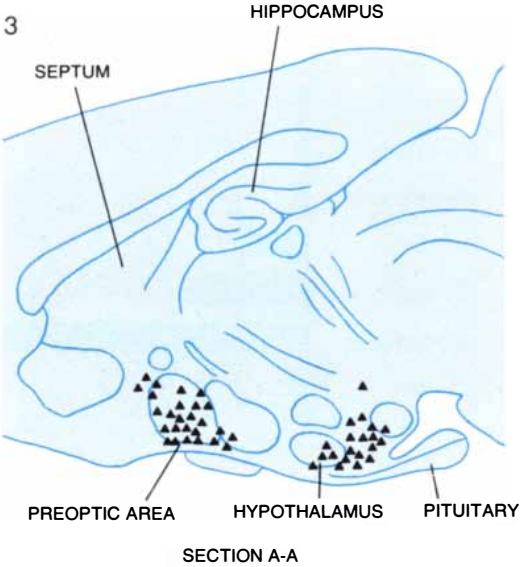
mitters released by adjacent neurons. There is little information on this important point, but the fact that hormone-sensitive cells in the brain have been localized should make it possible to obtain such information in the near future.

A possible model of how hormones modify the synaptic transmission of nerve impulses can be found in the ability of certain drugs to alter neurotransmitter function. For example, drugs that inactivate the serotonin system, which is itself inhibitory, have been observed to increase the lordosis response of spayed female rats primed with estradiol. On the other hand, inhibition of the noradrenergic system of the brain, which is itself also inhibitory, increases the output by the hypothalamus of corticotrophin-releasing factor (CRF), which in turn increases the secretion of ACTH from the pituitary. As I have mentioned, ACTH causes the adrenal glands to secrete adrenal steroids.

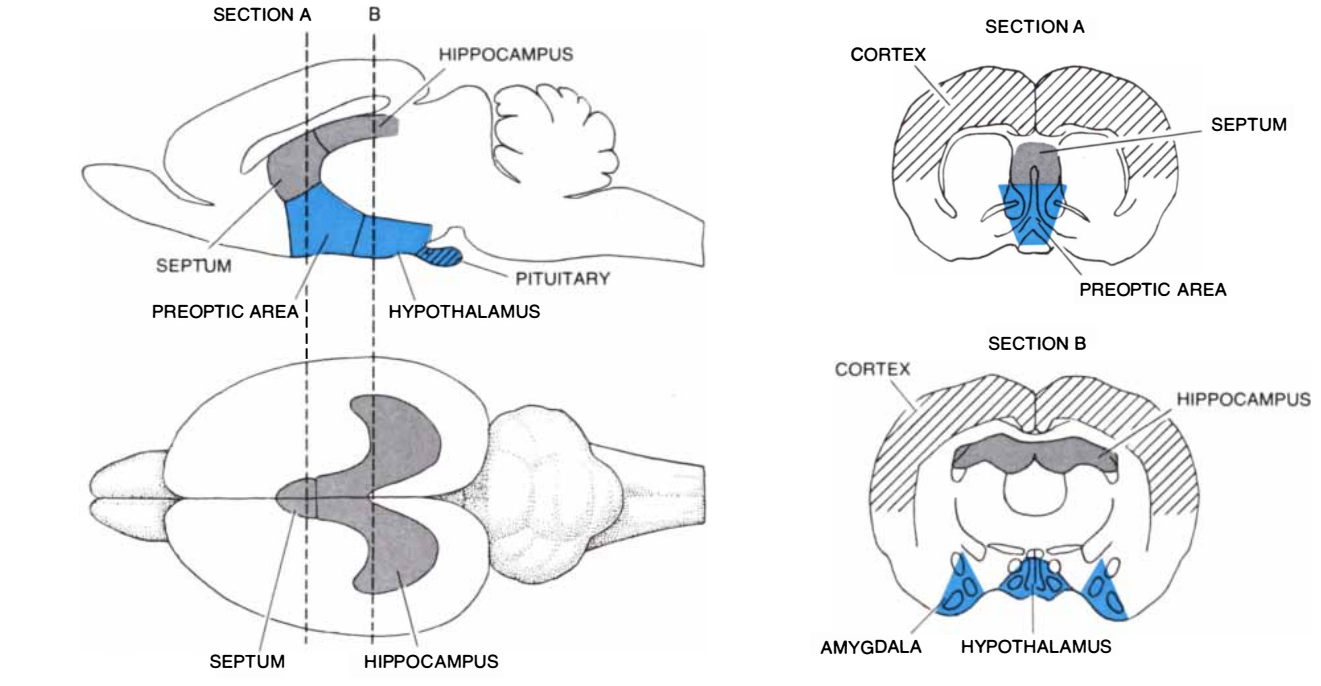
We can go one step further and consider

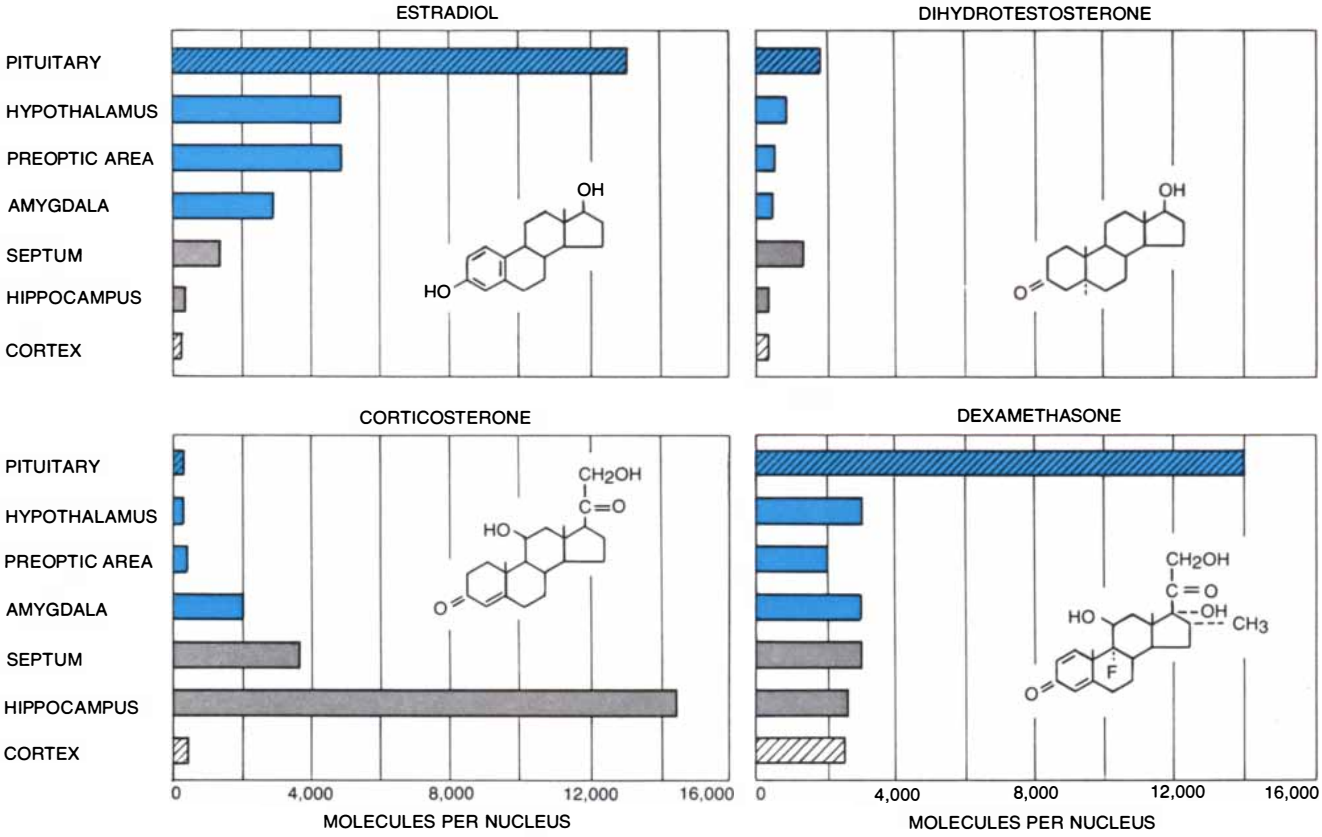



**ESTRADIOL-SENSITIVE NERVE CELLS in the brain of the albino rat are concentrated in the preoptic area, the hypothalamus and the amygdala. The black dots in sectional maps No. 1 and No. 2 indicate regions in the brain that were made particularly radioactive when animals were given tritium-labeled estradiol. The experiments were conducted by Pfaff and Melvyn Keiner of Rockefeller University. In a related study Robert D. Lisk of Princeton University examined the effects of implanting tiny amounts of estradiol directly in the preoptic area and in the hypothalamus. Typical results are illustrated in sectional map No. 3. The triangles indicate sites of implantation that elicited female sexual behavior or suppressed secretion of neurotransmitters to anterior pituitary, which controls the function of the ovaries.**

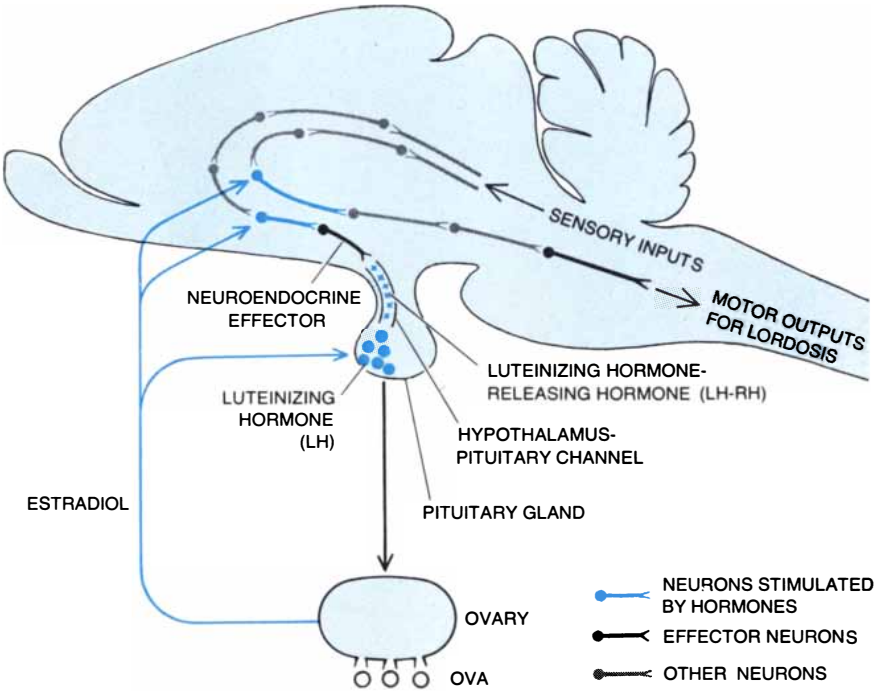



**DIFFERING RESPONSE OF BRAIN CELLS** to different kinds of steroid hormone has been studied by the author and his co-workers at Rockefeller University. They administered tritium-labeled hormones to male and female rats whose adrenals and gonads, the normal source of such steroids, had previously been removed. The animals were killed one or two hours later and their brains were dissected to remove the regions indicated in the diagrams at the top. The pituitary was also removed for study. The investigators isolated the cell nuclei from each sample and measured the amount of radioactive hormone present. The charts at the bottom show the number of hormone molecules per nucleus, averaged for all nuclei in each tissue sample. Autoradiograms reveal that the female sex hormone estradiol is bound to receptors in about 80 percent of all pituitary cells. For the brain areas with the highest affinity for estradiol (the preoptic area, the hypothalamus and the amygdala) the hormone is found in fewer than half of the cells. Dihydrotestosterone, a steroid that closely resembles estradiol, gives rise to an uptake pattern that is quite different. The adrenocortical steroid corticosterone is found primarily in the hippocampus. The chemically similar synthetic steroid dexamethasone, however, mimics the estradiol more closely than it does the adrenocortical steroid.

the consequences of such drug-induced changes in adrenal-hormone secretion. Higher levels of steroids could interact with the brain to alter mood, perception and sleep. This is an important consideration because drugs that act on neurotransmitter systems are widely administered in the treatment and management of human emotional disturbances and mental illness. Not enough attention has been paid to the secondary effects of their action on the delicately balanced endocrine system.

Even in the absence of drugs, changes in behavior can influence neuroendocrine secretion. The familiar human experience described as stress (caused by many factors, including fear, physical trauma, severe heat or cold and even extreme joy) has as a common denominator an increased secretion of adrenal steroids directed by the increased release of CRF and ACTH. The neuroendocrine systems governing reproductive functions are also subject to behavioral modification. For example, male rhesus monkeys subjected to decisive defeat by dominant males show dramatically lower levels of testosterone, whose secretion is directed by a hypothalamic releasing factor. When defeated males are exposed to female companions, however, the testosterone levels are rapidly restored to normal.




**CONTROL SCHEME depicts the role of neural and chemical signals in regulating the production of a particular steroid hormone, estradiol, and in eliciting a specific form of sexual behavior, the lordosis response. The latter, observed in female rats, is a downward arching of the back that facilitates mating. At the base of the brain a group of nerve cells, known as neuroendocrine effectors, is influenced both by sensory inputs and by the level of estradiol circulating in the blood. The neuroendocrine effector secretes into a capillary bed at the base of the hypothalamus a small polypeptide molecule: luteinizing hormone–releasing hormone (LH-RH). When LH-RH, carried by the blood, reaches the pituitary gland, it triggers the release of luteinizing hormone (LH), another polypeptide. The blood carries LH to the ovary, where it stimulates the secretion of estradiol and, if the quantity of LH is enough, causes ovulation. Estradiol travels in the blood to the brain and the pituitary, where it acts on receptors in target cells to modify the neural circuits controlling LH-RH secretion and the lordosis response. An important stimulus for the secretion of LH-RH arises from a biological clock that is internal to the animal. The clock, not represented in the illustration, responds to relative amounts of light and darkness.**

Although the effects of steroid hormones on the adult brain are normally reversible, steroids are also capable of giving rise to effects that are permanent for the life of the individual and that result in sex differences in both behavioral and neuroendocrine function. Let us consider these effects, which are aspects of the process known as sexual differentiation, and the hormone receptors that may be involved in them.

If the hormone is to have a permanent effect, it must be present during a brief sensitive period of early brain development. The critical period in human beings is during fetal life. In laboratory rats, however, the critical period comes during the first week after birth, when the testes of the male secrete testosterone. The testosterone initiates events leading to the sexual differentiation of the brain.

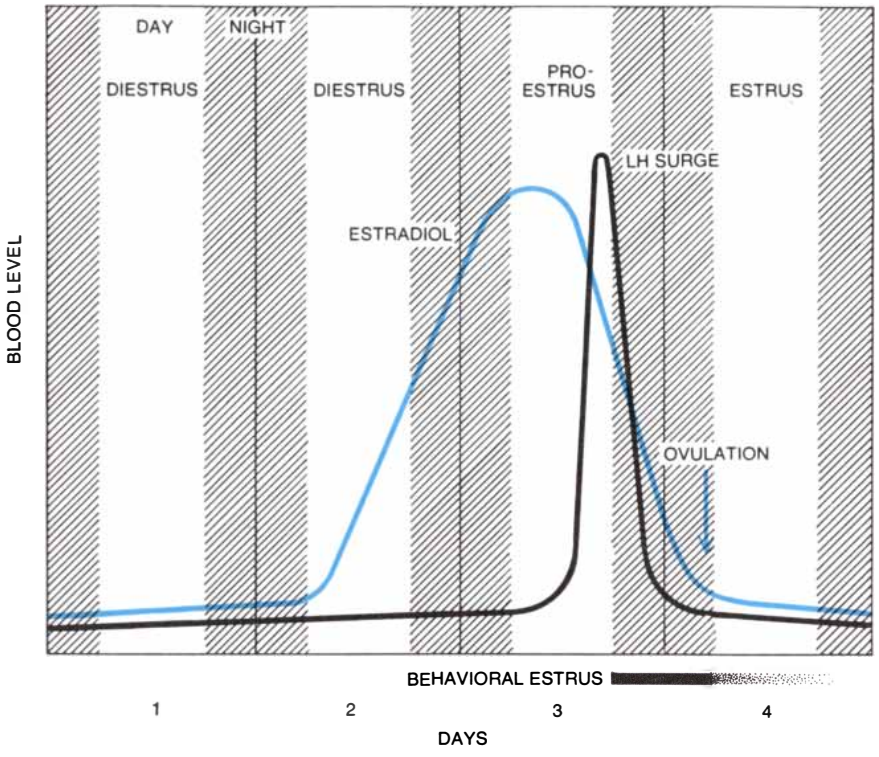
Since the rat brain is undifferentiated until shortly after birth, it has been possible to experimentally dissect the phenomenon by which steroids of the testes cause sexual differentiation. The adult male rat continues to show strong male sexual behavior and exhibits the female lordosis response only slightly even when it is castrated and given estradiol. If the testes are removed from a newborn male rat, however, its brain retains a female pattern of differentiation. As an adult the animal will show only weak male sexual behavior even after treatment with testosterone, and it will display a strong lordosis response when it is given estradiol. The two kinds of response resemble those of spayed but otherwise normal female rats given similar hormone treatments.

In contrast, a female rat given testosterone on the fourth day after birth will as an adult perform like a normal male in the tests for male and female sexual behavior. In other studies of early sexual differentiation it has been found that ovaries transplanted into a castrated newborn male rat or into a spayed newborn female rat will ovulate but that ovaries will not ovulate when they are implanted in a newborn female rat treated with testosterone or in a male castrated as an adult.

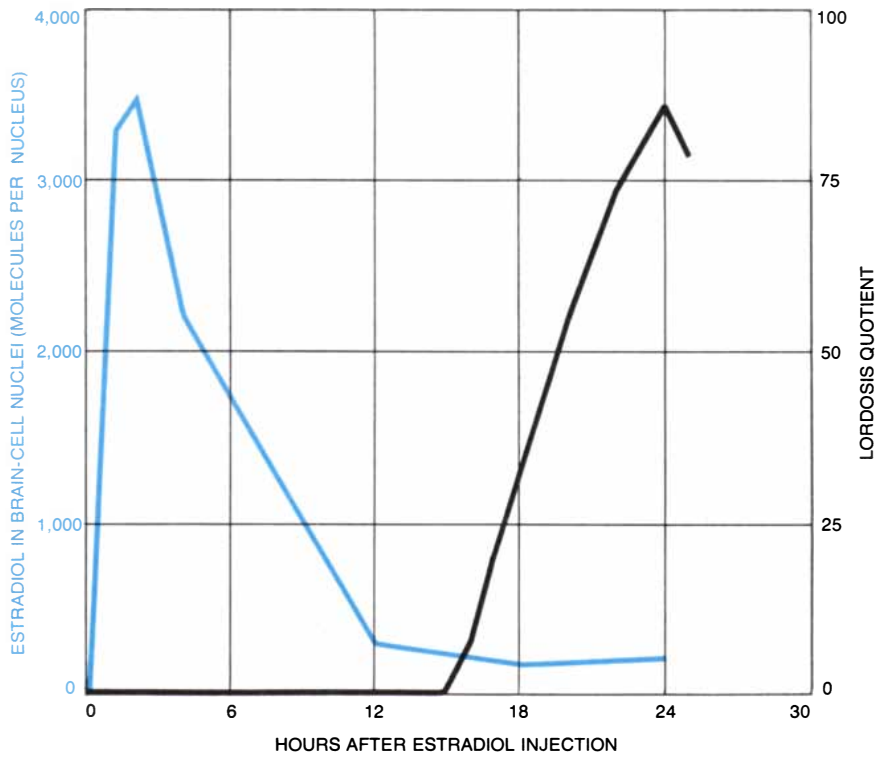
The permanent nature of sexual differentiation strongly suggests that testosterone influences the development of neurons and the formation of synaptic contacts with other neurons. These events may involve both cell replication (and therefore the synthesis of DNA) and the expression of genes (and therefore the synthesis of RNA and protein). A number of investigators report they have been able to block sexual differentiation with drugs that inhibit one or more of these synthetic events. Other workers, however, have been unable to get the same results. The discrepancy may be explained by the length of time the inhibitors are effective in relation to the duration of the exposure to testosterone. According to Gorski and his colleague Shinji Hayashi, microimplants of testosterone in the hypothalamic area of the brain must be left in place for 48 to 72 hours in order to bring about sexual differentiation. Therefore if the inhibitors were to be effective, they too would have to be present for a similar period. It is doubtful that inhibitors have been active for the required time in any of the studies so far reported. An additional complication is the fact that the inhibitors of the synthesis of DNA, RNA and protein block the synthesis of substances other than those thought to be stimulated by testosterone. The longer the inhibitors are allowed to act, the greater the likelihood is that nonspecific brain damage will occur.

In spite of the difficulties with such experiments, the participation of the genetic material in the sexual differentiation of the brain is virtually assured by the fact that genes direct the growth and differentiation of all living matter. A more critical issue is the location of the cellular changes that underlie these phenomena. Independent studies by Ronald D. Nadler of Emory University and by Gorski and Hayashi show that a tiny amount of testosterone implanted in the preoptic region and the hypothalamus of newborn female rats is sufficient to give rise to sexual differentiation of the brain.

Detailed information regarding the intracellular consequences of sexual differentiation has been provided by Geoffrey Raisman and Pauline M. Field of the National




**NORMAL ESTROUS CYCLE OF RAT causes females to exhibit estrus, or sexual, behavior every four days. Two days after estrus behavior, on diestrus Day 2, the estrogen level of the animal's blood begins to rise again, reaching a peak on the next day, proestrus, Day 3. The rising estrogen triggers a sharp rise in the level in the blood of luteinizing hormone (the "LH surge") on the afternoon of proestrus, causing ovulation to occur early in the morning of Day 4, estrus. Behavioral estrus, including lordosis response, which is also dependent on earlier estrogen secretion, can be stimulated by the male during the night between proestrus and estrus.**




**BRAIN ESTRADIOL LEVEL in female rats reaches a peak about 22 hours before the peak in lordosis behavior, according to the author's studies. The average number of molecules of tritium-labeled estradiol in the cell nuclei of the preoptic area, the hypothalamus and the amygdala is shown by the colored curve. Lordosis response (*black curve*) is expressed as the percentage of times a female rat facilitated a male's attempt to copulate by a downward arching of her back.**

Institute for Medical Research at Mill Hill in London. When they compared the fine structure of the neural connections of the preoptic area in adult male and female rats, they found a difference in the distribution of specific types of synaptic contacts. Castration of newborn male rats during the critical period, but not later, prevented the male pattern from emerging. Treatment of female rats with testosterone during the sensitive period, but not later, induced a male pattern of synaptic contacts in the preoptic area.

Tissue from the preoptic area and the hypothalamus of fetal mice can be cultured outside the body under artificial conditions for several weeks. It has been shown by Dominique Toran-Allerand of Columbia University that such tissue is exceptionally sensitive to the application of testosterone and estradiol during a period in culture that corresponds to the sensitive period for sexual differentiation in the living animal. The major effect of the two steroids is to enhance the outgrowth of the fibers of developing neurons. This fits well with the observations of Raisman and Field, because the number and geometry of the growing fibers will help to determine the pattern of synaptic connections.

To recapitulate, newborn male rats deprived of testosterone by castration show a female pattern of brain organization as adults. If newborn female rats are given testosterone, they exhibit male sexual behavior as adults. Paradoxically the female steroid estradiol is at least as potent as testosterone, and perhaps more so, in giving rise to male sexual differentiation when it is administered to newborn female rats. As we have seen, the brain of the adult rat possesses enzymes for converting testosterone into estradiol and dihydrotestosterone. The administration of dihydrotestosterone to newborn rats has no effect on sexual differentiation. If the brain of the newborn rat also possesses the enzymes for converting testosterone into estradiol, one can conjecture that estradiol is the agent responsible for the brain differentiation associated with male sexual behavior.

Naftolin and his co-workers, and Judith Weisz and Carol Gibbs of the Hershey Medical Center in Hershey, Pa., have demonstrated that the brain of the newborn rat does possess the enzymes for converting testosterone into estradiol. My colleague Lieberburg gave tritium-labeled testosterone to newborn male and female rats and recovered tritium-labeled estradiol in purified cell nuclei from the preoptic area, the hypothalamus and the amygdala. The amount of testosterone-derived estradiol in the cell nuclei ranged between 30 and 50 percent.

Hence the brain of the newborn rat has the enzymes to convert testosterone to estradiol and it also has a receptor mechanism for the product: estradiol. Further studies in my laboratory have substantiated the existence of a receptor mechanism for estradiol in the cell nuclei of the brain of the newborn rat. We were able to obtain direct

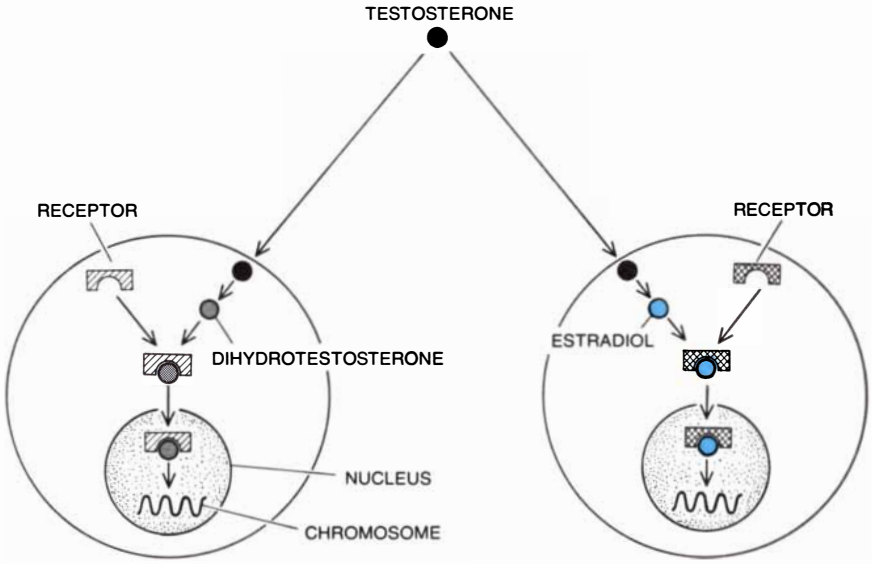
evidence for such receptors by injecting tritium-labeled derivatives of estradiol into newborn male and female rats. Such derivatives bind more effectively to the receptor sites in the animal than estradiol itself does. Cell nuclei isolated from newborn rats that had received the tritium-labeled derivatives contain large amounts of hormone attached to receptorlike proteins. In addition Michael Ginsburg and his co-workers at Chelsea College of the University of London and Linda Plapinger and Neil J. Maclusky in my laboratory have found a cytoplasmic estrogen receptor in the brain of the newborn animal and have shown that the receptor is depleted when radioactive estrogen is given to the animal. Evidently the cytoplasmic receptor migrates into the nucleus of the cell when it becomes loaded with the steroid.

The receptor system for estradiol in the brain of the newborn rat therefore resembles very closely, and may even be identical with, the receptor system in the brain of the adult rat, with the same anatomical distribution in the preoptic area, the hypothalamus and the amygdala. The major difference, according to our own work and that of Ginsburg's group in London, is the presence of estrogen receptors in the cerebral cortex of the newborn rat. These sites disappear between two and three weeks after birth and are virtually absent from the cerebral cortex of the adult rat. Their function remains obscure, but clearly it does not involve a response to estrogen derived from testosterone, because the cerebral cortex lacks the converting enzymes.

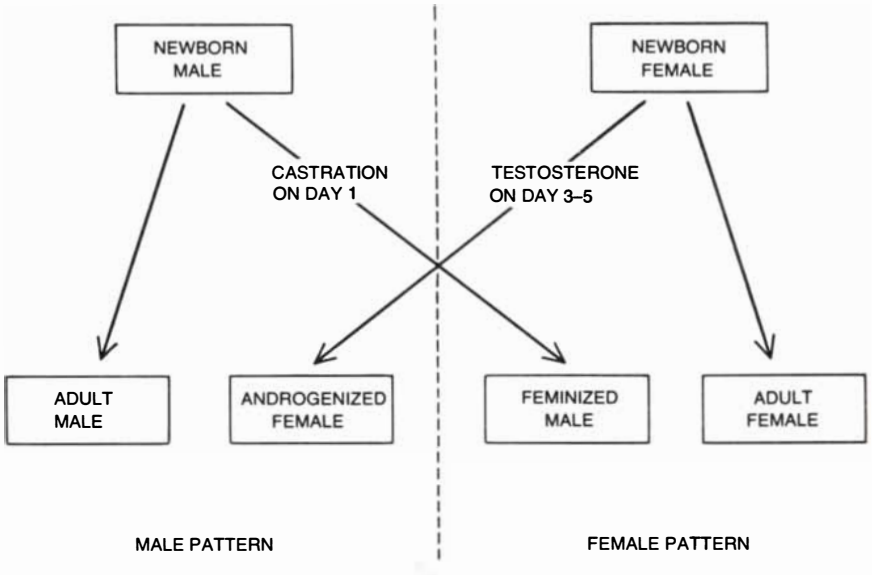
The hypothesis that the estrogen receptors of the preoptic area, the hypothalamus and the amygdala actually mediate sexual differentiation has stimulated a great deal of interest and research. Several reports from the laboratory of the late Peter McDonald of the Royal Veterinary College in London indicate that antiestrogens (drugs that compete with estradiol for the receptor sites and block its physiological actions) attenuate or prevent the sexual differentiation that is normally induced in newborn female rats by testosterone. Other published reports, however, fail to confirm this effect. Validation of the hypothesis thus awaits a conclusive experiment.

If estradiol administered to a female rat is so effective in giving rise to the male pattern of sexual differentiation, how is the female rat normally protected against its own estrogen and the estrogen of its mother? A major protective mechanism is an estrogen-binding blood protein, alpha-fetoprotein. Alpha-fetoprotein tends to keep the circulating estradiol from reaching the target neurons. Estradiol is able to reach its receptor sites in amounts sufficient to bring about sexual differentiation only if large amounts of it are given to the animal. Alpha-fetoprotein is manufactured by the fetal liver, and it persists, in declining amounts, during the first three weeks of postnatal life. My colleague Plapinger has found that alpha-fetoprotein is present in the brain of both male and female newborn rats, not as a part of the brain itself but rather as a constituent of the cerebrospinal fluid. Since alpha-fetoprotein does not bind testosterone, the testicular testosterone of males has unhindered access to the brain, where it can be converted into the estradiol needed to give rise to sexual differentiation.

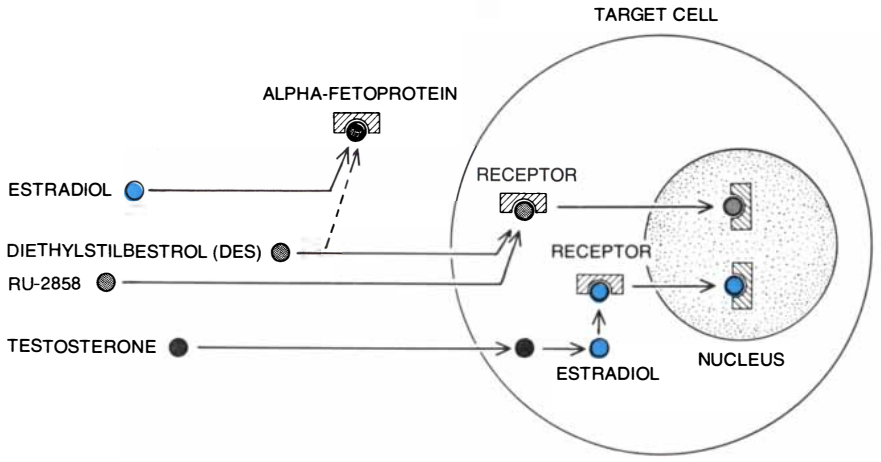
There are several synthetic estrogens that do not bind significantly to alpha-fetoprotein and therefore reach the estrogen-receptor sites in the brain of newborn rats even when they are administered in minute amounts. One of these estrogens, with the code name RU-2858, has been made available to us by Jean-Pierre Raynaud of the French pharmaceutical manufacturer Roussel-UCLAF. It is a form of estradiol with additional chemical groups added to the molecule. We find that RU-2858 is ef-




**TRANSFORMATION OF TESTOSTERONE TO ESTRADIOL and another steroid, dihydrotestosterone, is accomplished by enzymes in many target cells, including those in the preoptic area, the hypothalamus and the amygdala, but not in the pituitary. This leads to the paradox that a "male" hormone, testosterone, is converted into a "female" hormone, estradiol, which then exerts strong male effects in particular cells where transformation occurs. Dihydrotestosterone increases effectiveness of estradiol in restoring male sexual behavior in castrated rats.**



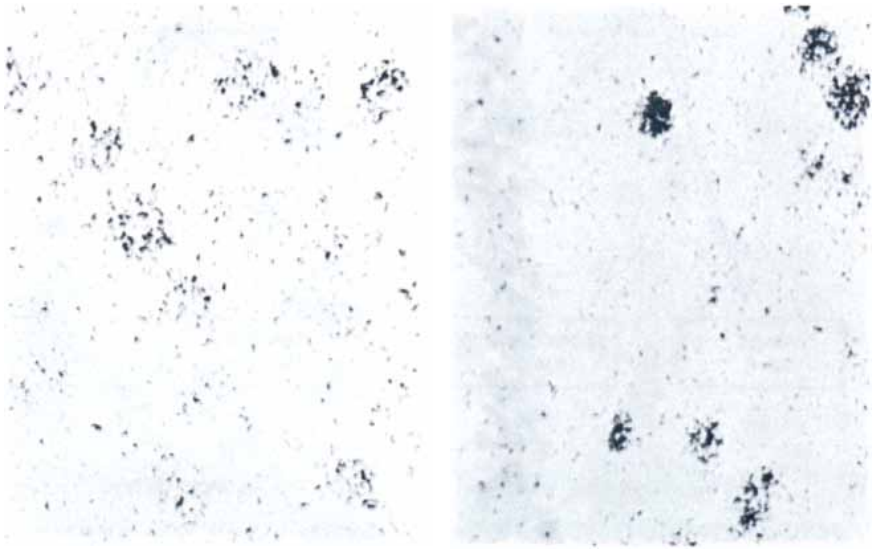

**SEXUAL DIFFERENTIATION of the rat brain takes place soon after birth. In newborn males testosterone, secreted by the testes, is converted by target cells in the brain into estradiol, which gives rise to a permanent "male" pattern of brain structure. If the male is castrated at birth, however, the sexual differentiation of nerve circuits in the brain fails to take place and the brain retains a "female" pattern. Administration of testosterone to a newborn female rat evokes a "male" pattern of brain circuitry as a result of the testosterone's being converted intracellularly into estradiol. The female's own gonadal secretion of estradiol is prevented from reaching the estradiol-responsive brain cells by the mechanism depicted in top illustration on next page.**




**ACCESS OF ESTRADIOL TO BRAIN is blocked in newborn female rats by alpha-fetoprotein, a substance present in the newborn animal's blood and cerebrospinal fluid for about three weeks. Two synthetic estrogens, diethylstilbestrol and RU-2858, are able to reach receptors in target cells because they bind weakly or not at all to alpha-fetoprotein. Similarly, testosterone gains access to target cells and is converted into estradiol, which interacts with estrogen receptors. Evidently it is estradiol from testosterone that evokes "male" pattern in brain of males.**

fective in loading the estradiol receptors in the brain of newborn rats at a dose less than a thirtieth of an effective dose of estradiol itself. Results obtained in McDonald's laboratory indicate that RU-2858 is also between 50 and 100 times more effective than estradiol in causing sexual differentiation in the rat brain. According to Raynaud, RU-2858 is also more effective than estradiol in stimulating the growth of the developing uterus in newborn rats. Hence its effects are by no means confined to the developing brain.

Synthetic estrogens such as RU-2858 have been made in an effort to find more effective means of controlling human fertility and of remedying the syndrome of inadequate estradiol secretion during pregnancy, which can result in miscarriage. Their action on the developing brain of the rat has created an awareness of the possible deleterious effects of such synthetic estrogens on the human fetus. Another synthetic estrogen, diethylstilbestrol, has in fact become the object of concern because of the abnormal incidence of vaginal and cervical cancer in young women whose mothers had received the hormone during pregnancy. Like RU-2858, diethylstilbestrol is capable of causing sexual differentiation of the rat brain when it is administered during the sensitive period. Since information on the physiology of the human fetus is limited, it would be premature to conclude that sexual differentiation and protection from estrogenic effects on the sexual differentiation of the brain operate identically in human beings and laboratory rats. Nevertheless, it is clear that synthetic estrogens present serious hazards to normal early development in both species.



**ESTROGEN-SENSITIVE NERVE CELLS in the brain of infant rats are revealed in these autoradiograms by the accumulation of tritium-labeled RU-2858, a synthetic estrogen, in the cerebral cortex (*left*) and hypothalamus (*right*). The experiment, conducted by Gerlach and Linda Plapinger in the author's laboratory, shows that in three-day-old female rats alpha-fetoprotein, which binds estradiol and therefore prevents it from reaching the cells that are responsive to estrogen, does not interfere with the access of RU-2858 to the two types of brain cell.**

Let me summarize briefly. Endocrinologists have discovered that steroid hormones have two quite different effects on the brain, both of them involving an action of steroids on the genetic material of the cell nucleus. On the one hand, hormones such as estradiol, normally regarded as being female hormones, are responsible for the reversible activation of the lordosis response and ovulation in adult female rats. On the other, when certain areas of the developing brain are exposed to hormones such as estradiol (or estradiol derived from the putative male hormone testosterone), there is a permanent change in the structure of the brain, resulting in a male pattern of behavior in the adult animal. If the developing brain of a newborn male is deprived of testosterone, say by castration, the animal's brain retains a female pattern of organization. The difference between the permanent responses to steroids in the newborn animal and the reversible responses in the adult must be due to the state of differentiation of the target neurons themselves at the time the hormone reaches them.

Since the genetic material, DNA, is the same in all cells of the body, the process of cell differentiation must involve the selective turning on of certain genes and the turning off of others. Under normal circumstances differentiation is irreversible for the lifetime of the tissue, that is, red blood cells do not begin to make neurotransmitters and brain cells do not begin to make hemoglobin.

According to this concept, testosterone or estradiol that reaches the nuclei of certain hormonally sensitive differentiating nerve cells during the critical period for the sexual differentiation of the brain provides a signal for activating certain genes and suppressing others. As a result the hormone may influence the pattern of the connections the affected nerve cells form with other nerve cells and thereby may determine the nerve circuits in part of the brain. Once these circuits are formed their basic structure is no longer susceptible to hormonal influence. During adult life the role of the hormone may be to alter the functional efficiency of the circuits. Hence even though certain genes may be turned on in a differentiated cell, they are not necessarily fully active at all times. Their activity may in some cases be modulated by hormones. On this view the estradiol that reaches the cell nuclei of adult neurons provides a signal for increasing or decreasing the activity of genes that are permanently expressed in that cell. In this way the hormone may be able to influence the functioning of developmentally fixed neural circuits that control, for example, sexual behavior. We must now discover what chemical properties of the target neurons are essential for the appearance of the behavioral response.

# About breast cancer and x-rays

**A hopeful message from industry on a sober topic**

One of every fifteen girls born will develop breast cancer, according to statistics. There is little evidence of change in this over the years.

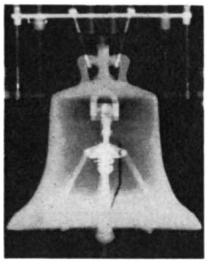
In the sixties, x-ray mammography was introduced. Previously 90% of breast cancers were found by the patient herself noting a lump. By the time a lump is noticeable, in 50 to 60% of cases, the cancer has spread to the lymph glands of the armpit. With spread to these glands, 36% of the women live another 10 years, as compared with 76% if medical intervention occurs when the cancer is still localized in the breast. (Obviously, self-examination is far better than no examination at all.)

On November 6, 1975 in New York the American College of Radiology and other interested groups briefed the press. The failure rate in mammography for women under 50 was reported to be about 10%; for women over 50, about 17%. One participant expressed the personal opinion that mammography can itself induce breast cancer, and stated the risk is small but not zero. On the basis of a mass screening program now in progress, he estimated that out of one million mammographic examinations, 20 cancers will be induced and 2500 existing cancers will be discovered at a stage where, with treatment, more than 85% of the women can expect to be alive five years later. This might be considered a benefit-to-risk ratio of 125:1.

The day after the press conference, at a medical symposium on breast cancer in Madison, Wisconsin, we announced a new film for mammography and a fluorescent screen with emission matched to the film sensitivity. The new film requires one-ninth the exposure of our previous mammography film. The film bears emulsion on only one side. The emulsion yields high contrast at low density. Only one screen is used, not a pair. Those improvements enhance the ability of film to show early calcifications and fibrous structures.

We mortals in industry would like to think we can help build that 125:1 ratio even higher.

**For some subjects, one simply pours on the roentgens**



*For the national birthday party,* we and another firm offered to radiograph the Liberty Bell before it was moved for better display. The offer was accepted. We used a 670-curie cobalt-60 source and exposed the entire Bell and yoke for 7½ hours one night. This necessitated flashing lights around Independence Hall and reinforced patrols by the Forest Service to keep nocturnal passers-by at a proper distance.

# SCIENCE AND THE CITIZEN

## *Enslaved Quarks*

It has been a triumphant year for the quark model of elementary particles: even some of the more subtle effects predicted by the model have been observed. The quarks themselves, however, have not shown up to claim their share of the glory. No one has yet observed a quark in isolation. That could, of course, mean only that no one has yet looked in the right place with the right instrument, but a more fundamental explanation is possible. Several recent theories suggest that no one has seen a free quark because quarks live in bondage.

The quark model explains a large class of particles, the hadrons, as composite structures made up either of a quark and an antiquark or of three quarks. The quarks in the hadron are bound together by a hadronic force field in the same way that the electron and the proton in a hydrogen atom are bound together by an electromagnetic field. Freeing the constituent particles of the hydrogen atom is a relatively simple matter: one need only apply enough energy to ionize the atom. It would seem that a hadron might also be "ionized" in order to free the constituent quarks. Theories of quark confinement assert that such ionization is impossible.

The electromagnetic field in the hydrogen atom obeys Coulomb's law, which states that the force between the particles declines as the square of the distance between them. At large distances the force is negligible. The most direct approach to explaining quark confinement is to postulate that the forces between quarks obey a different kind of law. The force must not decline as the square of the distance; in the simplest case it would remain constant, regardless of the distance between the quarks.

A force law of the appropriate form is embodied in two complementary principles called infrared slavery and ultraviolet freedom. The principles were derived from the basic field theory that describes the interactions of quarks by David H. Politzer of Harvard University, James D. Bjorken of the Stanford Linear Accelerator Center and others. The concept of ultraviolet freedom states that at close range (much smaller than the dimensions of a hadron) the forces between quarks are weak and the quarks behave as essentially independent particles. Behavior of this kind has been observed in high-energy collisions of hadrons with other particles.

Infrared slavery is the exact obverse of ultraviolet freedom. It holds that at larger distances (of the same magnitude as the size of the hadron) the binding forces become more important. The quarks no longer move independently but are welded together into a single entity: the hadron itself. It offends intuition that a force should become more effective with increasing distance, but infrared slavery seems to flow from the underlying field theory without contrivance. If it is correct, then completely separating two quarks would require an enormous amount of energy, and perhaps an infinite amount. Long before the quarks were actually separated, enough energy would have been supplied to create a new quark and antiquark, which would interact with the existing quarks to create another hadron. The attempt to isolate quarks only creates new hadrons.

Coulomb's law can be understood by imagining lines of flux that radiate from a charged particle. The density of the flux lines declines as the square of the distance, thus explaining the force law. The behavior of the field would be quite different if the flux lines were confined to a single dimension, so that they did not spread out in space but were channeled along a single line. The force between two particles connected by such a field would be constant at all distances. This notion is the basis of another theory of quark confinement, called the string model.

In the string model hadrons are made up of quarks bonded to the ends of a flexible string, which can be interpreted as a one-dimensional force field. The quarks determine most of the properties of the particle, but the string itself carries most of the energy and momentum. String models of those hadrons that consist of a quark and an antiquark are easily visualized: a single hank of string with a quark on each end will suffice. Models of particles containing three quarks would require some more complex arrangement. For the purpose of explaining the confinement of quarks, the most interesting property of the string is that its potential energy is proportional to its length. Separating two quarks by stretching the string therefore requires a large amount of energy. At some point the string must break, with the formation of new quarks on the broken ends. Again the result is the creation of additional hadrons.

A third theory, first proposed by Kenneth A. Johnson of the Massachusetts Institute of Technology, confines the quarks quite literally by placing them inside a bag. The rapidly moving quarks cannot pass through the fabric of the bag, but they do exert pressure on it, and thereby they inflate it. The only way to free a quark would be to greatly expand the bag, perhaps to macroscopic dimensions. The bag itself, however, has mass, or energy, which is proportional to its volume. Hence separating the quarks by increasing the size of the bag calls for ever larger expenditures of energy.

Yoichiro Nambu of the University of Chicago has pointed out that the string and the bag models are closely related. A bag can be thought of as a string made as thick as it is long. A string, on the other hand, could be constructed simply by spinning a bag until it becomes greatly elongated.

If any of these theories is correct, then it is not merely difficult or costly to isolate a quark; it is impossible. All three theories would be refuted, of course, by the emancipation of a single quark.

## *Threshold*

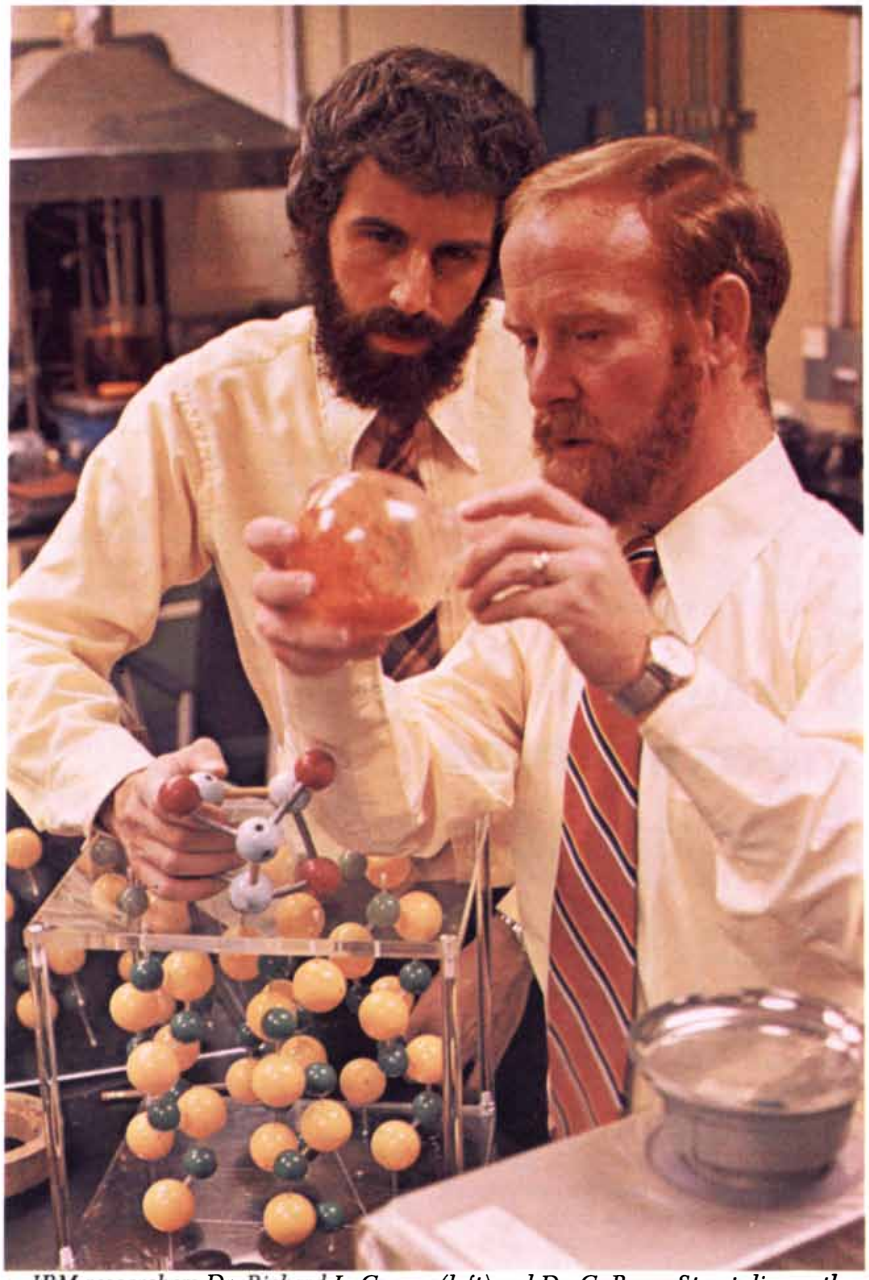
The series of formal arms-control agreements worked out by representatives of the U.S. and the U.S.S.R. over the past few years has met with widespread, if not always enthusiastic, support among arms-control advocates in the U.S. scientific community and in Congress. In spite of repeated expressions of discontent with the modest scope of some of the agreements and persistent reservations concerning the possible counterproductive effects of the prevailing "bargaining chip" approach to negotiating with the Russians, proponents of a more ambitious disarmament policy have generally ended up supporting such restricted bilateral pacts on the ground that, however imperfect they were, they were clearly better than no agreements at all.

The treaty limiting the size of underground nuclear explosions for peaceful purposes, signed on May 28 by President Ford and Secretary Brezhnev, may prove to be an exception to that rule. The new treaty was intended to complement the "threshold" treaty on underground nuclear-weapons tests signed by Secretary Brezhnev and President Nixon in 1974. Ratification of the latter treaty by the Senate was held up pending the resolution of the peaceful-uses "loophole" left in the original agreement. The new treaty has already been subjected to unusually harsh criticism by groups that can normally be counted on to back any arms-control and disarmament measure. For example, in a strongly worded statement issued in advance of the recent signing the Federation of American Scientists rated the two threshold test-ban treaties jointly as being "worse than nothing." And following the release of the text of the new treaty the Arms Control Association judged the accords "a disheartening step backward from responsible arms-control policies."

The attack on the two threshold treaties focuses primarily on the large size of the underground nuclear explosions that would be allowed under the proposed new regime. Both agreements set a limit of 150 kilotons for single nuclear explosions: roughly an order of magnitude greater than the force of the atomic bomb that destroyed Hiroshima in 1945. As many critics pointed out at the time of the original treaty signing in 1974, this level of testing bears no relation to the threshold at which underground nuclear tests can be reliably distinguished from natural earthquakes. Most seismologists today agree that the verification level for underground nuclear explosions is 10 kilotons or less. It is because of this wide disparity that the F.A.S. statement argues that the proposed 150-kiloton threshold "directly re-

# DP Science Dialogue

Notes and observations from IBM that may prove of interest to the scientific and engineering communities.



*IBM researchers Dr. Richard L. Greene (left) and Dr. G. Bryan Street discuss the crystalline structure of polysulfur nitride, the first polymeric superconductor.*

## The Polymer that Superconducts like a Metal

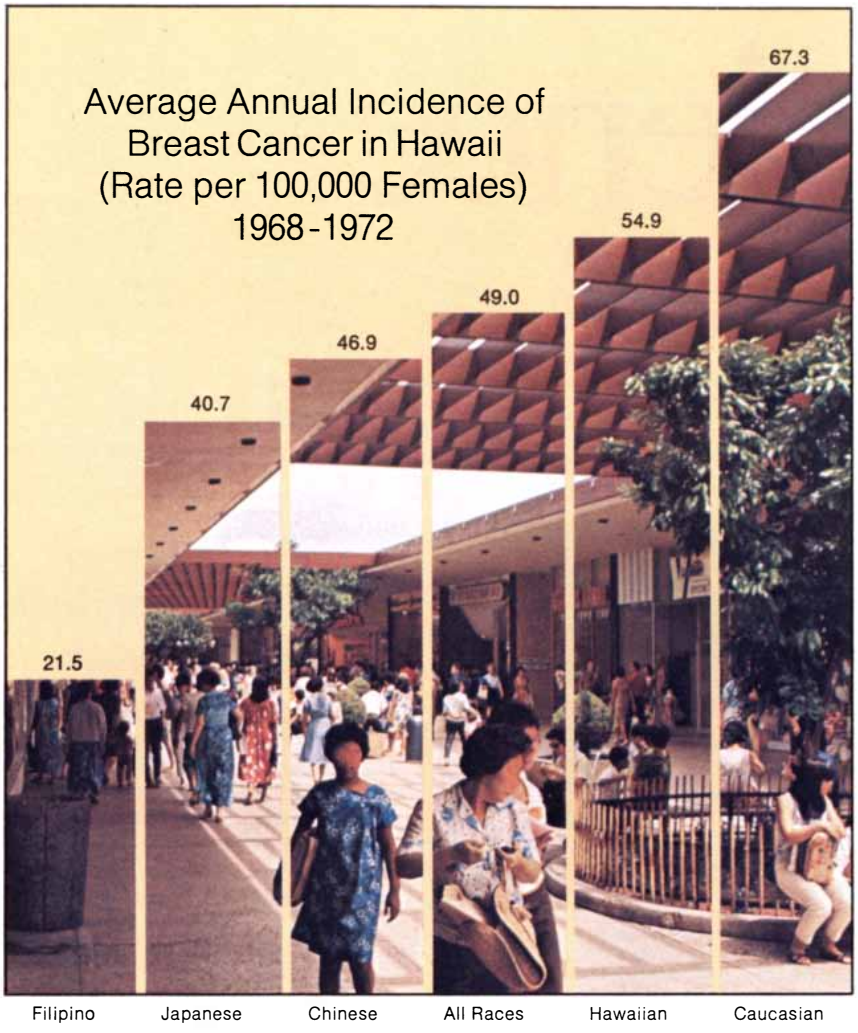
The search for new materials capable of achieving superconductivity has yielded an unlikely candidate—a polymeric solid composed of nonmetallic atoms. The substance, polysulfur nitride $(SN)_x$, conducts electricity like a metal at room temperature. Even more significantly, when it is cooled to 0.35 Kelvin, just slightly above absolute zero, the polymer becomes a superconductor: that is, it loses all electrical resistance.

Polysulfur nitride is the only polymer in which superconductivity has ever been observed. Its unique properties were first discovered during a series of experiments under a joint study agreement carried out by Dr. Richard L. Greene and Dr. G. Bryan Street, both staff members at IBM's San Jose Research Laboratory and by Dr. Laurence J. Suter of Stanford University.

Ordinarily, most polymers act as insulators rather than conductors. However, the molecular structure of polysulfur nitride in its crystalline form causes it to behave uniquely. The structure consists of chains of alternating sulfur and nitrogen atoms. The crystals are fibrous, with the chains running parallel to the fibers.

"Polysulfur nitride is an anisotropic, quasi-one-dimensional material, which means that it conducts electricity or reflects light much more readily along the chain direction than in other directions," explains Dr. Greene. "That is because the distance between the atoms is much shorter along the chain direction, and electrons naturally follow along that path, rather than jumping the longer distance from chain to chain. This anisotropic structure distinguishes $(SN)_x$ from typical metals which can

*(Continued on fourth page)*




*The unique racial mix in Hawaii gives researchers an opportunity to study the environmental and genetic factors which may influence susceptibility to various forms of cancer. This graph is based on 910 cases of intraductal breast carcinoma reported to the Hawaii Tumor Registry from 1968-1972.*

# Computerized Data Base Aids Cancer Researchers in Hawaii

Is there any relationship between a woman's height and weight and the possibility that she may contract breast cancer? Or between racial origin and the tendency to get a specific form of cancer? Could diet or occupation have any influence on a person's susceptibility to cancer?

These are all questions currently being researched at the Cancer Center based at the University of Hawaii. Scientists and doctors trained in a wide range of disciplines including biology, chemistry, genetics, epidemiology, biophysics, immunology and virology are studying the correlation among many factors which may be related to causing cancer.

The Center, funded largely by the National Cancer Institute, maintains a large computerized data base stored in the University's IBM System/370 Model 158. It includes information such as the birth and marriage records and ethnic backgrounds of over 200,000 families living in Hawaii.

## Many Factors Involved

"We begin with the belief that there is more than one condition which can influence susceptibility to cancer," explains Dr. Lawrence H. Piette, Director of the Cancer Center. "These conditions may include exposure to or the presence of a specific virus, the existence of a particular carcinogen in the environment and/or a genetic predisposition to the disease. Any one of these factors alone will not necessarily cause cancer, but in combination they are more likely to increase the probability the disease may occur."

Hawaii provides an excellent "laboratory" for studying cancer because of the unique racial mix of the population. Data collected by the Tumor Registry program, part of the state's Department of Health, indicate that the seven major racial groups in Hawaii – Japanese, Filipino, Chinese, Korean, pure Hawaiian, part Hawaiian and Caucasian – have different incidences of cancer at different ages, despite the similarity of environment.

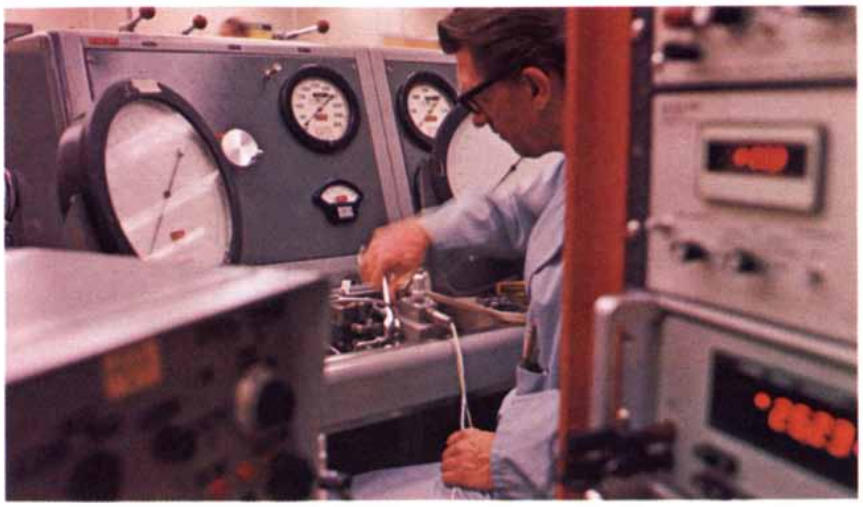
## Heredity or Environment?

"We want to determine the relationship between the environmental and genetic factors in connection with the disease," says Dr. Piette. "For example, we know that the incidence of breast cancer in Japanese women who have migrated to Hawaii is higher than for those who have remained in Japan. On the other hand, the propensity of the offspring of Hawaiians of Chinese ancestry to get a rare form of cancer called nasal pharangeal carcinoma seems only slightly affected by environmental change. In both cases, we'd like to find out why, now that we have identified broad correlations."

For instance, the data base has been used to test the validity of the hypothesis that women who are taller and heavier relative to the average for their race show a higher risk of getting breast cancer. First postulated by a team of Dutch researchers, this theory appears to be substantiated for the women whose records form the Hawaiian data base. However, Dr. Piette cautions that simple correlations only tell part of the story. Many other factors, such as the age of a woman during her first pregnancy and her estrogen profile, may also be very significant in determining susceptibility to breast cancer.

"We were fortunate that Hawaii already had good record keeping programs," says Dr. M. P. Mi, a geneticist and director of data communications. "Our goal now is to incorporate additional kinds of data such as blood type and fingerprints. Most people aren't aware that fingerprints can help determine racial origin, a significant fact in a population with extensive intermarriage.

"Most of our work is still in the preliminary stages," comments Dr. Mi. "As we move into multivariate analysis—correlating many factors—we will be able to get increasingly specific results. We feel our work can help develop hypotheses which can be followed up in later studies. The more we know about the disease, the better our chances will be for earlier diagnosis by identifying high risk groups and, in many cases, effecting cures."



*Product testing at Hydraulic Research, a Textron company, at Valencia, California. Engineering simulations are conducted interactively with the computer using VM/370-CMS.*

# Virtual Machine is "Something Else" for Hydraulic Research

Under the now-familiar concept of virtual storage, real computer storage is multiplied many times over to increase the number of applications the computer can handle. Less well known, perhaps, is the virtual machine concept, whereby the entire machine—the computer system itself—is similarly multiplied.

A virtual machine is a simulated functional equivalent of a real IBM System/370. It consists of a virtual CPU or central processing unit, together with virtual storage, virtual input/output devices and a virtual console. Under the IBM Virtual Machine Facility/370 (VM/370), every user appears to have such a dedicated system so that with concurrent users, multiple computing systems appear to exist. With VM/370 users can run the operating system of their choice. For example, they might choose among DOS/VS, OS/VS1 or OS/VS2.

Interactive time sharing is at the heart of VM/370 through the Conversational Monitor System (CMS), by means of which each user is given frequent slices of computer time. At Hydraulic Research and Manufacturing Company of Valencia, California, some 85 engineers employ VM/370-CMS in the design of high-technology aerospace products.

Using seven terminals to communicate with the company's Model 145 computer, the engineers simulate such factors as stress and thermal reactions by means of mathematical models. Thousands of simulations may be needed for each project. The engineers program their own requirements in conversational mode with the computer, eliminating coding and keypunching.

"The result is improved engineering performance through more comprehensive simulation," says Samuel X. Garcia, president. "Interactive computing through the virtual machine facility gave us a big boost in productivity. We're designing better products because of it—and we're doing it faster."

And Reed F. Simpson, director of management services, points out that the engineers like the response they get and their ability to make online corrections in their sessions with the computer. "This avoids time-consuming reruns with attendant delays and frustrations," he says. "It's a big factor in keeping morale high and in getting a job done to an engineer's satisfaction."

# New IBM Program Personalizes Computing

Many scientists, engineers, statisticians and other researchers have found that the computer can be an indispensable aid in solving a wide range of problems. But most professionals are so busy that they've sometimes found it easier to ask for the help of the data processing department to meet their computing needs, rather than trying to write programs themselves. With the development of simple computer languages, however, there has been a marked move towards direct communication with the computer through terminals readily accessible to users.


Now a new IBM interactive program product called Virtual Storage Personal Computing (VSPC) makes it easier for people without data processing backgrounds to use the computer themselves. VSPC is not a computer language, but rather a time sharing subsystem which simplifies the preparation and execution of programs as well as such functions as data entry and retrieval.


VSPC's simple English-like commands such as "LIST", "RUN" or "FIND" are used in conjunction with one of three popular computing languages. Users can solve complex mathematical equations, evaluate design alternatives, or analyze large files of stored data—just to name a few of the capabilities VSPC makes much easier. For a more complete discussion of VSPC, just write for our booklet, "Personal Computing". Please send the request, on your letterhead, to the IBM Corporation, Department 83F, Data Processing Division, 1133 Westchester Avenue, White Plains, New York 10604.

The languages for which VSPC was specifically designed are VS APL, VSPC FORTRAN and VS BASIC. Of the three, VSPC FORTRAN is the classical language used for scientific and engineering applications, although VS APL is also being used with increasing frequency. VS BASIC is geared for business and statistical problems.


VSPC can be used with all of the larger IBM System/370 computers. It saves time and enables people to test a variety of alternatives, make changes on the spot and follow a line of thought to its conclusion—without interruptions or long delays.

*The final touches are being applied to a helicopter at Bell Helicopter Textron in Fort Worth. The aircraft was designed with the help of computer simulations.*

# Bell Helicopter Gets a Lift from Computer-Aided Design

A helicopter blade spins at 300 revolutions a minute as its turbine engine runs at 6,000 RPM. A multistage transmission, designed and manufactured by Bell Helicopter Textron, accomplishes a twentyfold reduction to provide lift for the craft. That capability alone makes it a very complex mechanism, but at Bell there is an additional requirement: the transmission must be able to run dry of oil for thirty minutes and survive.

That level of performance requires very precise design parameters. Bell's engineers have been using the Fort Worth company's IBM System/370 Model 168 to help produce reliable, cost-efficient helicopters. Much of the designing is done by engineers who interact directly with the computer via twenty-five IBM 3277 and 2741 terminals which are linked to the Model 168 under the Time Sharing Option (TSO) and OS/VS-SVS.

"With interactive computing, we've been able to increase the productivity of many engineers by a factor of four," says Joe Red, chief of scientific and technical computing. "By evaluating more options in the same time, they can minimize technical risks."

At Bell, computer-aided design is used to model everything from human factors like legroom and headroom to helicopter "survivability" under the most turbulent conditions. The company has developed over 500 specific application programs which run the gamut from designing the smallest gears to simulating the flight characteristics of the entire aircraft.

For example, computer analysis is particularly valuable in determining the optimal dynamic and structural configuration of the helicopter. All helicopter rotors vibrate to some degree; the object is to create a design which minimizes the amount the fuselage vibrates without weakening the aircraft structurally. This is accomplished by mounting the rotor and transmission at the middle of a nodalized beam and suspending the fuselage from node points along that beam. A mathematical model is used to determine the most efficient beam design. Factors like the size, weight, strength and vibration characteristics of the beam are varied.

The entire fuselage must also be analyzed for each new model. "First, we make an educated guess at the best preliminary design," says Red. "Then using the computer and NASTRAN, NASA's structural analysis program, we calculate the load factors of each part of the model separately. A complete detailed fuselage model may comprise 4,000 elements. Generally, the simulation requires several iterations to achieve the desired frequency.

In addition to structural analysis, the computer is also used to formulate the "egg shell" configurations – the geometry of an aircraft's skin. That mathematical definition is subsequently used for numerical control machining. In the manufacturing area, the computer keeps track of manpower requirements, operations plans and parts production schedules.

"Interactive computing and a comprehensive data base," says Red, "have helped us design and produce rotorcraft with the classical aerospace virtues –maximum strength, minimum weight and as much payload as possible."

# Polymer...

*(Continued from first page)*

conduct equally well in any direction."

"We are interested in learning more about $(SN)_x$, because many of the so-called 'organic metals' also exhibit anisotropic quasi-one-dimensional structures," adds Dr. Street. "The more we understand about $(SN)_x$ the better we may be able to explain why certain organic metals also have the ability to conduct electricity."

So far, no organic polymers have been made which are metallic or superconducting. However, there is some speculation that certain organic materials might be able to support superconductivity at temperatures considerably higher than typical metals. To date, the highest temperature at which any material has been known to superconduct is 23 Kelvin. (Room temperature is 300 K.) Because the apparatus to cool materials to extremely low temperatures is cumbersome and expensive, achieving superconductivity at higher temperatures is very desirable.

Among the anisotropic conductors, $(SN)_x$ is also unique because it never goes through the so-called Peierls transition–the abrupt switch from acting like a conductor to acting like an insulator. The Peierls transition is exhibited by all known quasi-one-dimensional conductors when their temperatures are lowered beyond a certain point. For example, one "organic metal" becomes increasingly conductive until it is cooled to about 58 Kelvin when it abruptly becomes an insulator.

"There are still many unanswered questions about $(SN)_x$," says Dr. Greene. "We intend to investigate the effect of moving chains closer together and possibly modifying the crystalline lattice in other ways to see if we can make the polymer superconduct at higher temperatures. The more we can explain about the mechanism by which $(SN)_x$ conducts and why it avoids the Peierls transition, the closer we will be to producing organic conductors which also exhibit superconductivity."

*DP Science Dialogue is concerned with topics which may prove of interest to the scientific and engineering communities. Your comments and suggestions are welcome. Just write: Editor, DP Science Dialogue, IBM Data Processing Division, 1133 Westchester Ave., White Plains, N.Y. 10604.*

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neges" on the declared U.S. policy of more than a decade, which repeatedly emphasized that the only obstacle in the way of a comprehensive test-ban agreement was the problem of verification. "The clear implication of this position was that any threshold agreement would be reached at a threshold level no higher than the capabilities of national verification demanded.... In the context of verification there is no justification whatsoever for a level as high as 150 kilotons; quite the contrary, this level has been set by military considerations. Neither military establishment needs to test larger explosions."

What makes the proposed threshold worse than nothing, in the view of the F.A.S., is that the two agreements, if they are ratified by the Senate, are likely to take the subject of a comprehensive test-ban treaty "off the political agenda." The statement adds: "If a dozen years of saying we wanted limits bounded by national verification capabilities could not lead to better than this, the present reversal of policy is likely to end the matter for the foreseeable future." As for the widely expressed hope that the proposed level of testing can subsequently be lowered, the F.A.S. contends that "the linkage between peaceful and military uses makes doubly unlikely any reduction of the 150-kiloton ceiling." The effect of the proposed treaties is also held to be "counterproductive" with respect to the problem of nuclear proliferation, since it will be seen by the "nuclear-tending powers" as a "bad joke" and since it "advances the notion that peaceful uses are plausible," thus encouraging new nuclear powers "to justify bombs as intended for peaceful uses."

Regarding the official claim that the new peaceful-uses treaty creates a good precedent in allowing on-site inspection in certain strictly prescribed (and somewhat improbable) situations, the F.A.S. statement considers this argument to be "entirely misleading." The statement goes on to say: "On-site inspection is a precedent whose time has passed. Since the early 1960's when this was an issue, satellite inspection of aboveground events has made on-site inspection unnecessary for strategic-weapons treaties. And seismological advances have narrowed, virtually to equivalence, the tests which can be detected but not identified. Thus there is little to which on-site inspection is relevant in the 1970's."

For these reasons the F.A.S. regards the proposed threshold treaty as "a mistake," concluding "with regret" that they "cannot support its ratification." The effect of the opposition of the F.A.S. and similar groups on the prospects of ratification of the treaties by the Senate is uncertain at this stage.

## *Illuminated by Neutrons*

One of the major challenges in cell biology today is the mapping of supramolecular structures such as membranes and ribosomes. These structures are made up of protein building blocks of differing size and shape that spontaneously come together in a process of recognition and association, giving rise to an assembly of the lowest possible energy.

A few years ago the solutions to these molecular jigsaw puzzles seemed remote, since most protein assemblies fall into the gap in scale between the traditional domains of biochemistry and cell biology. Ribosomes, for example, the cytoplasmic particles that coordinate the translation of messenger RNA into protein, have so far been impossible to crystallize and are hence unsuitable for X-ray-diffraction analysis. Moreover, only the vague outline of their shape can be seen in the electron microscope.

Recently, however, investigators have begun to apply antibodies and reagents that link neighboring proteins to map supramolecular assemblies with encouraging, if limited, results. And now Donald M. Engelman and Peter B. Moore of Yale University, in collaboration with Benno P. Schoenborn of the Brookhaven National Laboratory, have developed a neutron-scattering technique that promises to be a powerful tool in exploring the middle ground between the molecular and the supramolecular levels of biological organization.

Engelman and his colleagues have been primarily concerned with determining the spatial arrangement of proteins in the ribosome of the bacterium *Escherichia coli*. Like other ribosomes, the *E. coli* ribosome consists of two subunits that separate and rejoin at different stages in the cycle of protein synthesis. Engelman and his colleagues have concentrated on the smaller subunit, which consists of one copy each of 21 different protein molecules together with a single long strand of ribosomal RNA.

The neutron-scattering technique developed by the Yale-Brookhaven collaboration has many similarities to X-ray crystallography but differs from it in that the technique is applicable to randomly oriented particles in solution. In addition neutrons are unlike electrons or electromagnetic waves in that they interact principally with atomic nuclei and therefore can differentiate between isotopes of a given element.

Since hydrogen is ubiquitous in biological molecules, deuterium, its heavy isotope, is used for labeling the ribosomal proteins. Engelman and Moore have found that by deuterating individual proteins it is possible to make certain parts of the ribosomal assembly more "visible" to a neutron beam than the rest. The reason is that deuterium, with a nuclear structure different from that of ordinary hydrogen, scatters neutrons in a qualitatively different way.

How is the labeling accomplished? Since ordinary hydrogen and deuterium are biochemically identical, *E. coli* bacteria grown in heavy water (deuterium oxide) will incorporate the heavy isotope into their proteins. Ribosomal particles synthesized in the presence or absence of deuterium are then fractionated into their component proteins and reconstituted in a series such that each small ribosomal subunit in a given suspension incorporates a pair of deuterated molecules in addition to 19 molecules containing ordinary hydrogen. When the ribosomal proteins and RNA are mixed in vitro, they combine spontaneously into biologically active ribosomal subunits.

Suspensions of ribosomal subunits containing labeled pairs of protein molecules are then placed in a beam of low-energy neutrons produced by the Brookhaven fission reactor and reflected from a crystal to eliminate all the neutrons except those of a single wavelength, or energy. As the beam passes through the sample, the scattered neutrons are intercepted and counted as a function of the angle of deflection. According to a theory originally developed in 1915 by Peter J. W. Debye to account for X-ray scattering by a diatomic gas but easily applicable to neutron diffraction, the scattering curve includes an oscillating interference contribution whose periodicity is related to the center-to-center distance separating the two theoretically spherical proteins. If the proteins are close together, the interference curve has widely spaced peaks and valleys; if they are far apart, the oscillations move closer together.

With the aid of a computer it is possible to estimate the distance between the deuterated protein pairs in the reconstituted ribosomal subunit by measuring the degree of "rippling," or interference. The determination of a series of pair separations can then be used to reconstruct the spatial organization of the entire structure by triangulation.

Mapping of the small ribosomal subunit with this technique is proceeding apace, and the results will be a major step toward the still remote but now attainable goal of extending knowledge of cell structure and function from the molecular level to the biological level, thereby bridging the gap between the domains of biochemistry and cell biology.

## *State of the Child*

Large numbers of New York City children are inadequately nurtured by poverty-stricken one-parent families, are poorly educated by schools they often do not attend and are implicated in a juvenile-justice system that "seems to offer scarcely any protection, fairness or wisdom." These are among the broad findings of a two-year study by the Foundation for Child Development, "an attempt to gather and disseminate as much knowledge as possible about the conditions of New York City children." The investigators wanted to develop a set of social indicators that would measure social conditions and show trends over a period of time, much as standard indicators such as unemployment rates and per capita income measure economic conditions. It was not easy. "New York City and State spend millions of dollars in compiling numbers, but the information systems are fragmented and primarily responsive to the administra-

tive needs of individual agencies. Most of what is now collected is only incidentally usable to measure what is achieved for child or family."

The report by Trude W. Lash and Heidi Sigal nonetheless brings together some striking statistics. In 1970 just under half of all the city's children (less than 18 years old) lived in a "poverty area"; a fifth of them lived in families with incomes below the officially designated poverty line. In 1973 almost 28 percent of the children were in one-parent families headed by the mother, compared with one child in 10 in 1960; the increase is the result of higher rates of separation, desertion and divorce as well as of out-of-wedlock births, which accounted for more than a fourth of all live births in 1974 compared with about one in 16 in 1955. The infant-mortality rate in the city, once lower than that in the U.S. as a whole, has been somewhat higher since 1960, with the rate for black and Puerto Rican infants higher than the rate for whites. In 1973 there were 57 murders of children 14 or under in the city; homicide ranked fifth as a cause of death in the age group.

In 1975 more than half of the public school children in grades two through nine were reading below grade level. The average daily attendance rate has been decreasing, most sharply in the academic high schools, where fewer than three-fourths of the students were present daily during the 1973–1974 school year. Suspensions, most often for "aggressive behavior," have risen steadily. The dropout rate is up. There is more vandalism and in-school crime. There is more crime in general too: more than three and a half times as many children under 16 were arrested for violent crimes in 1974 as were arrested in 1960. The juvenile-court system finds it increasingly difficult to place offenders in a suitable institution; children adjudged "delinquent" are less likely to be institutionalized than "persons in need of supervision": children charged by a parent with such misconduct as staying out too late at night.

As the authors commented, "the data on every page indicate program shortcomings and the need for reform and change." The findings point toward the need not only for local responses but also for a national policy supportive of families and children. As a more limited objective, the authors insisted that better coordination of data-collection and information programs among city agencies, departments and systems "could save millions of dollars and would tell us far more than we know now about the people of the city and the effectiveness (or lack of it) of programs that serve them."

## *Cheops Plays Chess*

Chess players have taken some satisfaction from the knowledge that after more than 20 years of effort by computer experts to devise programs for playing chess, the best programs have not advanced beyond a class-B level, or roughly the level of middle-range tournament amateur chess players. The computer chess programs carry such names as Chaos, Ostrich, Treefrog and Etaoin Shrdlu. The U.S. computer chess championship is held by a program developed at Northwestern University called Chess 4.4. The world championship is held by Kaissa, a program written at the Institute of Control Science in Moscow.

The early optimism of chess programmers was based on the assumption that computers would be able to examine all possible moves and countermoves for several moves ahead. In fact, highly ingenious algorithms have been developed for searching enormous "trees" of variations and for pruning the trees expeditiously to speed up the search. In the typical three-minute period allotted to a move, a fast computer can examine from 50,000 to 500,000 positions. In contrast a human master or grand master will rarely examine more than 100 positions. His skill lies in selecting the few most promising moves and examining them to a greater depth than a computer can. Usually the computer search goes to a depth of only four or five plies (half-moves); occasionally it goes to eight or 10 plies. The reason is the exponential growth of the tree of variations as the search is deepened. If for each 10 half-moves there are 10 plausible countermoves, a five-ply search involves 100,000 possible moves. One of the developers of the Kaissa program remarked to an American programmer, "If we can achieve a 15-ply search, we can rule the world."

Perhaps the most ambitious effort to raise the caliber of computer chess is being jointly sponsored by the Artificial Intelligence Laboratory and the Laboratory for Computer Science at the Massachusetts Institute of Technology under the direction of Richard D. Greenblatt, who developed the first of the modern chess programs, known as MacHack, in the late 1960's. Greenblatt and his colleagues have built a special-purpose computer called Cheops (for chess-oriented processing system), which is designed to supply a "brute force" backup for a "sophisticated" program. A sophisticated chess program is one that evaluates the fundamental board position at each stage of the game and is provided with a set of criteria for selecting the most promising moves from a given position. The difficulty is that even grand masters cannot agree on such criteria; some would say the number of them is virtually infinite. The role of Cheops is twofold: to examine the moves proposed by the sophisticated program to see if they contain hidden blunders and to see on its own if large-scale tree-searching can come up with a good move overlooked by the sophisticated program. Since Cheops is solely concerned with the gain or loss of pieces, the sophisticated program is responsible for all positional play.

Cheops consists of 2,200 integrated-circuit chips containing among other things two arrays representing the 64 squares of a chessboard: an "origin" array and a "destination" array. Each array has 64 output lines to indicate whether a particular square is occupied and by what piece. Cheops can be asked, for example, to "light up" all the squares to which a given piece can move or all the squares on which the piece can make a capture. Because Cheops can indicate the occupancy of 64 squares simultaneously on each operating cycle of 200 nanoseconds, it can examine 150,000 positions per second. Thus in three minutes it can examine more than 25 million positions. Meanwhile the sophisticated program, running on a Digital Equipment KL10 computer, will be examining 40 positions per second among carefully selected variations. The complete program integrating the sophisticated program with the brute-force Cheops one is still being written. Later this year Greenblatt hopes to test the completed program against highly rated human players in the Cambridge-Boston area.

## *Sumerian Supernova*

In the last issue of *Scientific American* F. Richard Stephenson and David H. Clark described how certain historical records of Europe, the Arab lands and the Far East indicate that over the past 2,000 years seven supernovas—gigantic stellar explosions—were observed on the earth [see "Historical Supernovas," by F. Richard Stephenson and David H. Clark; SCIENTIFIC AMERICAN, June]. Now George Michanowsky, a student of Sumerian writings, has found evidence that perhaps 6,000 years ago the ancient Sumerians observed an even more conspicuous stellar explosion: a relatively close supernova in the southern constellation Vela.

Michanowsky has translated a cuneiform tablet of the Sumerian period as describing a brilliant new star in the Sumerian equivalent of Vela. Writing in *Explorers Journal,* a publication of the Explorers Club, he says that the Sumerians named the star Mul Nun-ki. It was considered sacred to E-A, the god of the southern ocean (today's Persian Gulf). From other tablets Michanowsky has determined that the position of Mul Nun-ki was between the stars Gamma Velorum and Zeta Puppis.

It appears highly likely that there was a supernova in Vela at about that time. Today the constellation is the site of a powerful X-ray source (designated Vela X) that is probably associated with a pulsar, or rapidly rotating neutron star (designated PSR 0833–45). The X-ray source and the pulsar are surrounded by the luminous wisps of a huge expanding gaseous nebula. Moreover, the pulsar lies between Gamma Velorum and Zeta Puppis.

From the rate at which the pulsar is slowing down it is calculated that it was probably set in motion between 11,000 and 6,000 years ago. If the Vela supernova exploded toward the end of that time, it would almost certainly have been visible to the Sumerians. The pulsar is less than 500 parsecs (1,630 light-years) from the solar system. The pulsar at the center of the Crab Nebula, which is a remnant of the brilliant supernova of the year 1054, is between 1,500 and 2,000 parsecs away.

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*The PocketCom components are equivalent to 112 transistors whereas most comparable units contain only twelve.*

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**The PocketCom's small size results from a breakthrough in the solid state device that made the pocket calculator a reality. Mega scientists took 112 transistors, integrated them on a micro silicon wafer and produced the world's first transceiver linear integrated circuit. This major breakthrough not only reduced the size of radio components but improved their dependability and performance. A large and expensive walkie talkie costing several hundred dollars might have only 12 transistors compared to 112 in the Mega PocketCom.**

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*The PocketCom can be used as a pager, an intercom, a telephone or even a security device.*

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# The Direct Reduction of Iron Ore

*Methods of making steel without smelting ore in a blast furnace are becoming increasingly economic where steelmaking facilities of modest scale are needed, notably in the developing countries*

by Jack Robert Miller

The iron ore from which iron and steel are made is an oxide, that is, a chemical compound of iron (Fe) and oxygen (O). Common forms of ore are hematite ($Fe_2O_3$) and magnetite ($Fe_3O_4$). For the ore to be made into iron the oxygen atoms must be separated from the iron atoms by the process known as reduction. The separation is usually achieved by causing the oxygen to react with carbon, hydrogen or carbon monoxide, leaving the iron free as a metal. In most conventional steelmaking processes the ore is smelted, yielding a pig iron containing reduced elements and a slag containing all the oxidized and unreduced substances. The pig iron is melted and refined in a steelmaking furnace. In this procedure the reduction of iron ore is regarded as an incidental intermediate step, and the reduction process is sometimes termed indirect. During the past few years, however, the ancient practice of direct reduction, in which the oxygen is removed from the iron without a melting step, has been improved and accepted to the point where it has become an important technology for steelmakers, particularly in developing countries.

The earliest known methods of extracting iron from ore involved direct reduction. In *De re metallica,* published in 1556, Georgius Agricola described three ways of melting iron, writing that the "first" of them, "a direct reduction of malleable iron from its ore," was "the primitive method [in which] the heat produced a pasty mass." Some 2,500 years earlier iron objects had been made by hammering such pasty masses of sponge iron, so named because the removal of oxygen from iron ore without melting leaves a honeycomb microstructure that resembles a sponge. The sponge iron was made by putting charcoal and iron ore in a shallow hearth, in which intense heat was built up by directing a jet of air at the burning charcoal. The temperature did not get high enough to melt the iron, which has a melting temperature of 1,538 degrees Celsius (2,800 degrees Fahrenheit), but it did melt the impurities in the ore, leaving the reduced iron in the form of a hot lump that could be removed from the fire and worked.

Over a long period of time the hearth evolved into a stack as its sides became higher and its bed of charcoal (later coke) and ore became deeper. The force of the blast of air was increased. Among the results were higher production of iron and lower consumption of fuel, since gases moving upward from the hot region preheated and prereduced the ore. As the temperature increased, the iron absorbed more carbon, with the result that the melting point of the iron was lowered and the iron then melted. This evolution led in time to the modern blast furnace, which is today the predominant means of reducing iron ore.

The molten iron emerging from a blast furnace is relatively impure, having picked up carbon and sulfur from charcoal or coke and silicon from impurities in the ore. For the iron to be made into steel (defined as iron with a carefully controlled carbon content of 1.7 percent or less) the sulfur, the silicon and the excess carbon must be removed. This task is performed in such familiar structures as the Bessemer converter, the open-hearth furnace, the electric-arc furnace and the basic-oxygen furnace.

Conventional steelmaking practice, involving the blast furnace and oxygen-blown converters, is well suited to production on a large scale. A single blast furnace is likely to have a capacity of from 7,000 to 10,000 tons of pig iron per day. Such an installation costs upward of $70 million, plus a nearly equal amount for coke ovens and other supporting facilities. Capital outlays of that magnitude can be justified only by the huge tonnages a blast furnace produces, outputs far exceeding the markets that most developing countries can hope to have for many years. The "miniplant" steelworks, however, with a direct-reduction unit to make sponge iron and an electric-arc furnace in which to convert the sponge iron to steel, can be built with an annual capacity of 100,000 tons or less. The necessary capital investment is proportionately lower, which is why direct reduction is of particular interest to many developing nations.

## A Century of Development

The idea of direct reduction as an alternative to the conventional way of making iron and steel is not new even in the developed countries. In 1869 William Siemens, who a dozen years earlier had designed the first open-hearth furnace and who 10 years later would introduce electric-arc melting, began experiments to extract steel directly from iron ore. He reduced a mixture of crushed

**DIRECT-REDUCTION PLANT is operated by Sidbec at Contrecoeur in the Canadian province of Quebec. It consists of two modules, each of which is identifiable by a tall shaft with a charging conveyor that runs from the ground to the top of the shaft. The module**

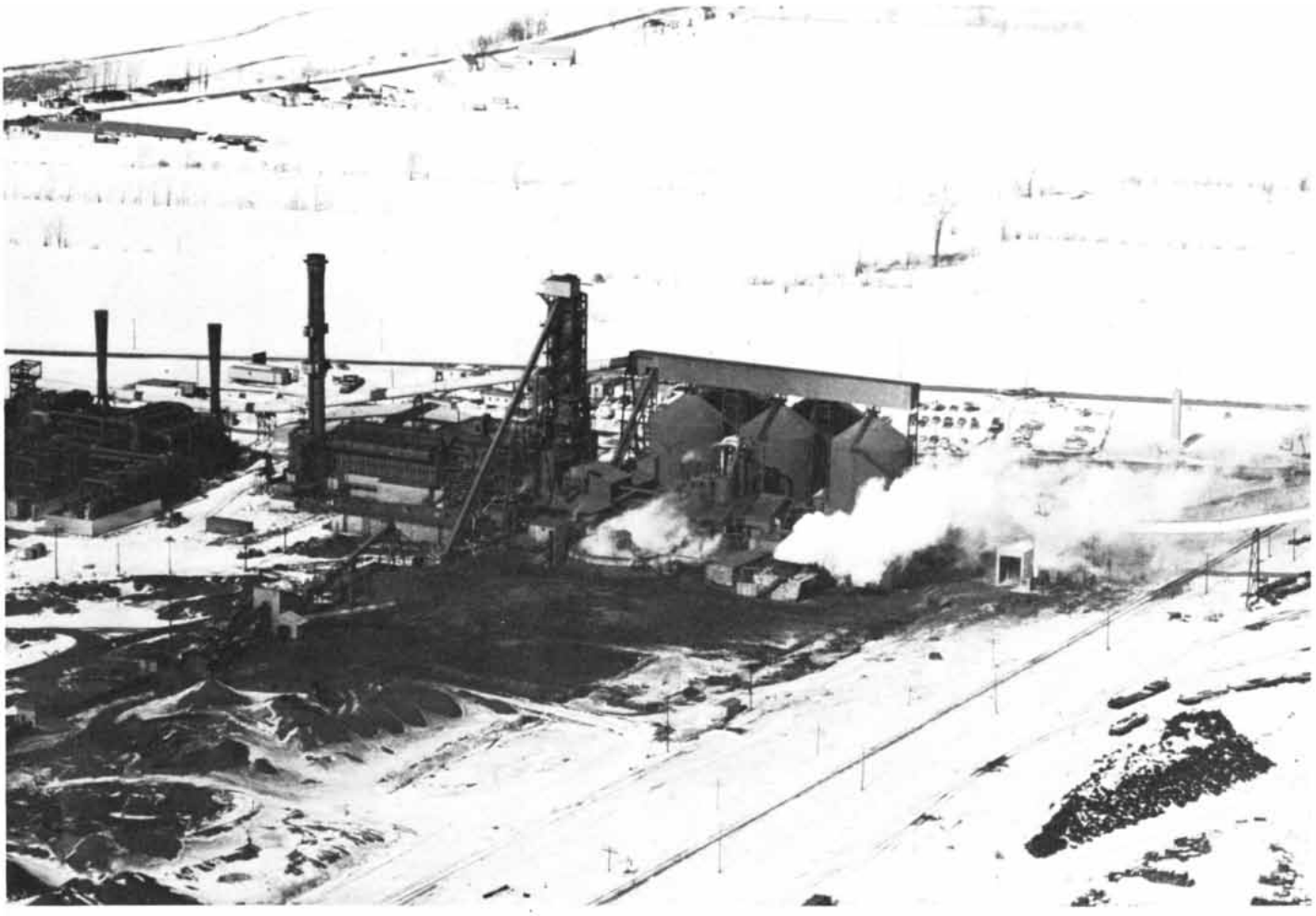
ore and fuel in a rotating cylindrical furnace. The spongy iron that emerged was passed down a duct lined with refractory material and plunged into a bath of liquid pig iron on the hearth of a steel-melting furnace. Reporting the results to the Iron and Steel Institute in 1873, Siemens expressed the hope that "the direct process may be carried on with great practical advantages as regards economy of fuel, saving of labour, and quality of material produced."

During the next four years Siemens built and operated three horizontal rotating direct-reduction furnaces. In 1877, however, he abandoned the project because "the cost of the iron bars produced was too high and their composition too variable." The problem of quality was caused largely by sulfur and phosphorus picked up from the raw materials that were available in Northamptonshire, where Siemens had erected the furnaces. He believed such difficulties could be avoided at plants located closer to richer ores and cleaner fuels.

The physical nature of what Siemens was trying to do can be explained with the help of a diagram that shows the changes in the oxygen and carbon content of an iron ore as the temperature rises in a furnace [*see illustration on page 77*]. In the conventional method of making iron and steel the ore is heated and melted during its passage down the shaft of a blast furnace. At a temperature of about 1,050 degrees C. the oxides have been stripped of their original oxygen content of approximately 30 percent. By the time the temperature has reached 1,550 degrees the materials originally charged into the blast furnace are fully molten in the hearth of the furnace. There the melt separates into two layers: liquid slag on top of molten pig iron, with such reduced elements as carbon, manganese, silicon, sulfur and phosphorus in the iron and oxidized components (such as calcium oxide, silica, alumina, sulfur, manganese and some iron) dissolved in the slag. As tapped from the furnace the pig iron has an iron content of from 90 to 95 percent and a carbon content of from 3.5 to 4.3 percent. It is ready to be refined in a steel-melting furnace, where all but a few tenths of the carbon absorbed during smelting is removed and impurities carried over from the charges of ore and fuel are lowered to acceptable levels.

Siemens hoped to remove the oxygen completely while the iron ore was still in a solid state. Recognizing that the resulting sponge iron would contain all the gangue (the rocky material in the ore) and impurities of the original mineral, he planned to use very high grades of iron ore. Presumably he intended to introduce minor amounts of carbon and other substances into his directly reduced material as it was worked and finished into bars, thus producing steel in a single step.

Unfortunately the world has few supplies of ore of the quality required to meet Siemens' objectives of the 1870's. Nearly 50 years later the availability in Sweden of the richest ore then known, together with electricity at low cost, provided favorable conditions for a renewal of interest in direct reduction. Two processes (the Wiberg and Hoganas processes) that were invented in the 1920's still serve to produce minor ton-

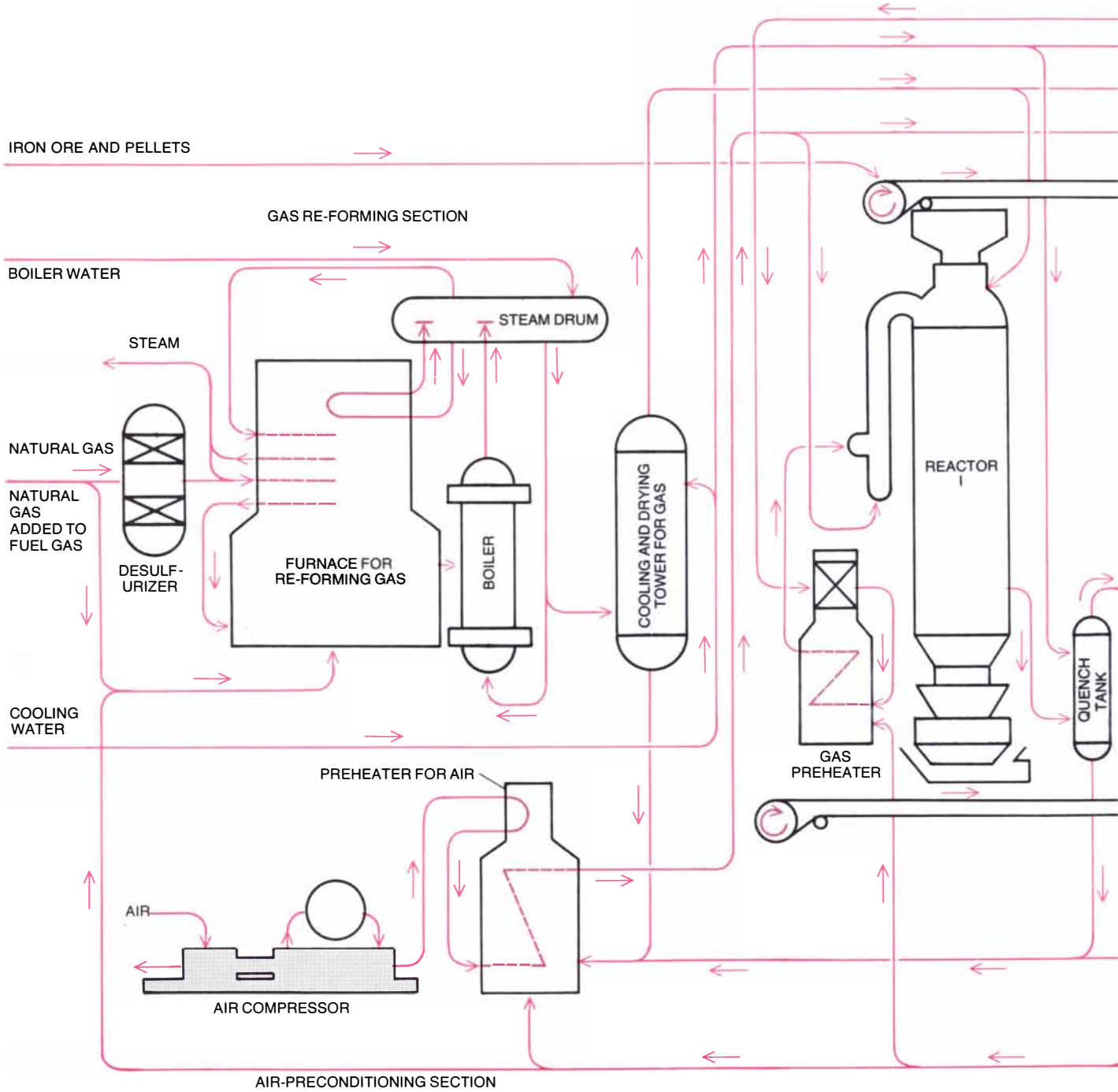


**at the right has been in operation since 1973, producing 400,000 tons of directly reduced iron per year. The module at the left is under construction; its capacity will be 650,000 tons per year. The plant employs the Midrex direct-reduction process, in which a charge of lumps of iron ore and pellets of iron oxide is loaded into the shaft through the conveyor and then descends through a stream of hot reducing gas. In this photograph piles of ore and pellets lie in the foreground of the operating module. Between the two shafts, associated with one tall stack and two shorter ones, are units where gas is re-formed. The silos at the right store reduced iron; each silo has a capacity of 7,000 tons. The white structure sloping upward to the right of the silos houses a belt conveyor carrying reduced iron to a nearby steelmaking facility.**

nages of iron powder from which small parts of intricate shape are formed under high pressure. The Swedish experience demonstrated, however, that for making steel on a commercial scale it would be necessary to melt directly reduced sponge iron so that the gangue could be removed during refining. The extra cost generated by this step curbed any general interest in direct reduction for some 25 years.

About 1950 a break in the situation came with the establishment of the electric-arc furnace as a major means of making steel. The electric furnace differed fundamentally from the Bessemer process that had dominated steelmaking from 1870 to about 1910, from the open-hearth process that had held the lead for the next 50 years and from the top-blown oxygen converter that is the industry's main steel-refining practice now. The last two methods work best at refining large heats of liquid pig iron in a two-step transformation from iron ore to steel, whereas the electric furnace is ideally suited for smaller charges of solid steel scrap.

By 1950, anticipating substantial increases worldwide in the demand for steel, the industry was looking for new sources of better raw materials and for improved technical procedures. (The increases have indeed occurred: in 1950 the worldwide production of steel was 190 million tons and last year it was 650 million tons.) Direct reduc-



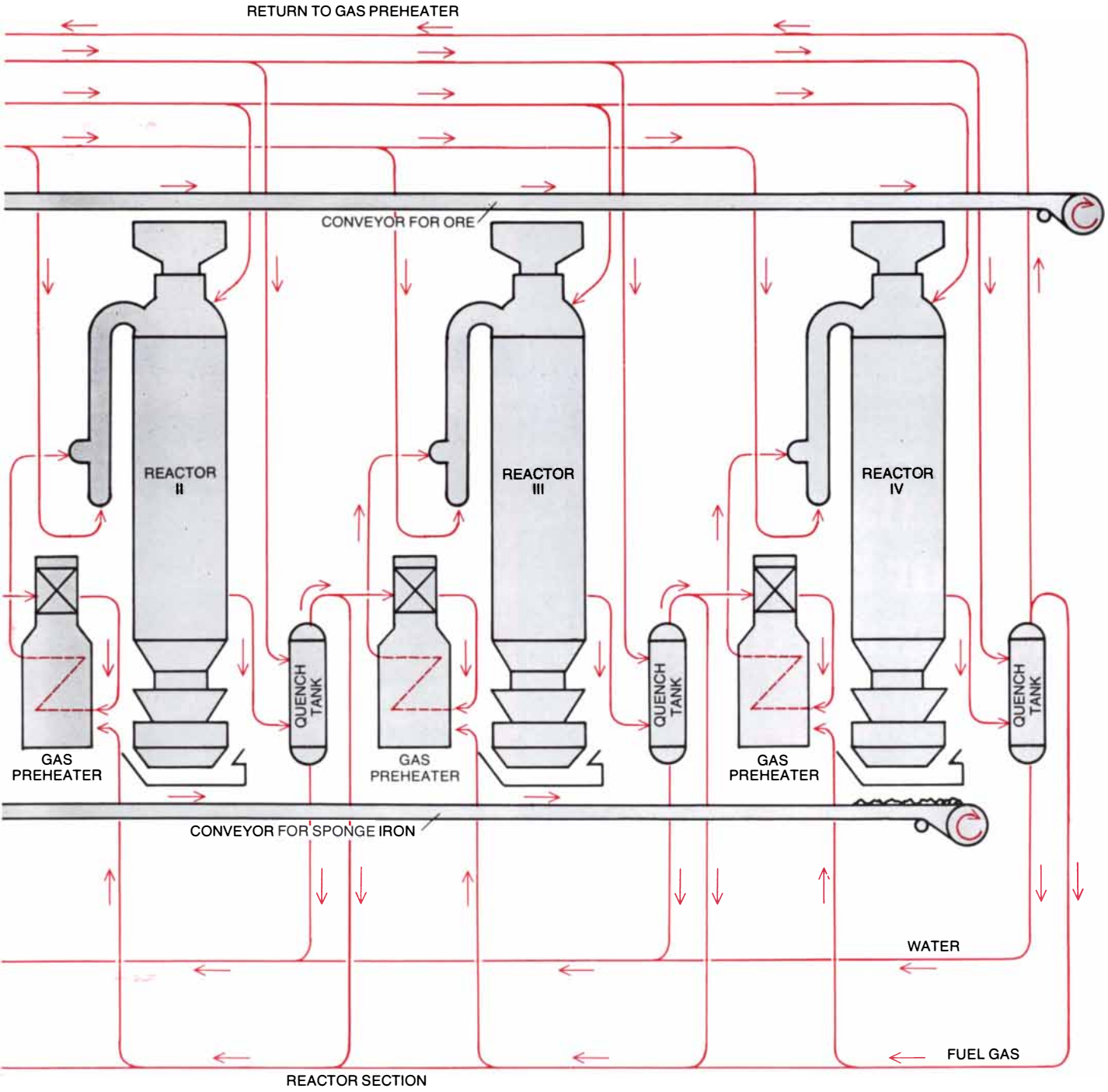

**HOJALATA Y LAMINA PROCESS, usually abbreviated HyL, is named for the Mexican steel company that built the first plant incorporating the process in 1957. The process uses a gas to reduce iron ore, that is, to remove the oxygen that is associated with the iron in the ore, leaving the iron as a highly metallized material that can be made into steel by refining it so that its carbon content is 1.7 percent or less. An HyL unit consists of four reactors, which operate independently but in series. The four reactors depicted here can be assumed to be respectively in the loading stage, the initial-reduction stage, the final-reduction stage and the cooling stage. At the outset a charge of ore or pel-**

tion coupled with electric-furnace melting suggested possibilities for meeting both goals. Nearly 100 direct-reduction schemes were examined by iron and steel producers between 1950 and 1975. About a dozen of them have survived intensive study and trials at the pilot-plant level. Some of the processes are now in use commercially, and several plants based on other designs are under construction.

In any direct-reduction process the transformation of iron ore into sponge iron is accomplished by the removal of oxygen from the iron oxides of the ore as a result of a reaction wherein the oxygen is made to combine with a gas (hydrogen or carbon monoxide) or with solid carbon. The process is termed gaseous direct reduction or solid direct reduction depending on the state of the reductant.

Directly reduced iron is not usually a finished product. It is a highly beneficiated iron ore that can be regarded as prereduced for further processing to iron or steel. The level of prereduction is measured by the ratio of the product's content of metallic iron to its total content of iron; the ratio, expressed as a percentage, is called the degree of metallization.

The mechanism of gaseous reduction can be described in terms of a small spherical mass with a core of hematite, a surrounding layer of magnetite, a further shell of wüstite




**lets is loaded into the reactor from the top. During initial reduction preheated and partially spent gas from the reactor that has just completed final reduction is passed through the stationary bed of ore, preheating it and partly reducing it. In final reduction fresh, preheated gas from the reactor that is in the cooling stage is introduced, and the major part of the reduction takes place. In the cooling stage cool reducing gas from the gas re-forming section (*left*) completes the reduction, adds carbon to the reduced material in controlled amounts and lowers the temperature. The resulting sponge iron (so named because it has a spongelike microstructure) is unloaded onto a conveyor belt.**

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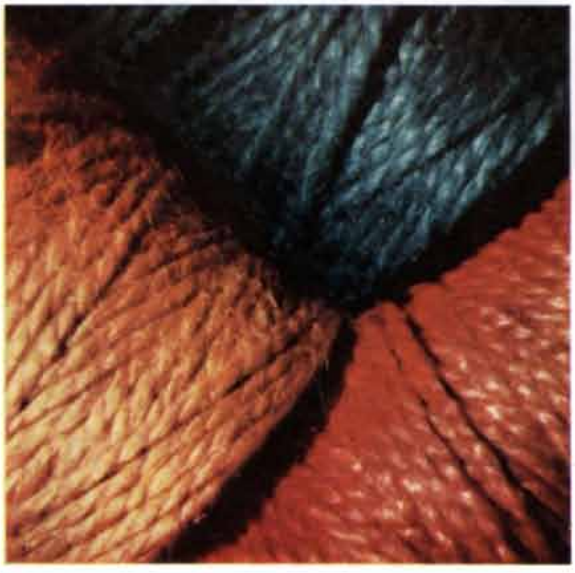


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# The SX-70 System from Polaroid

(FeO) and finally a porous outer surface of iron. The reducing gas is posited as moving readily through the external layers to the particle's center of hematite, from which it then diffuses outward. The ultimate result of the reactions occurring at the three interfaces is an outwardly directed chain of oxygen displacement that leaves either water vapor or carbon dioxide and reduced iron as the end products. The chemical exchanges at each boundary are similar; for wüstite reacting with carbon monoxide the reaction is $FeO + CO \rightarrow Fe + CO_2$.

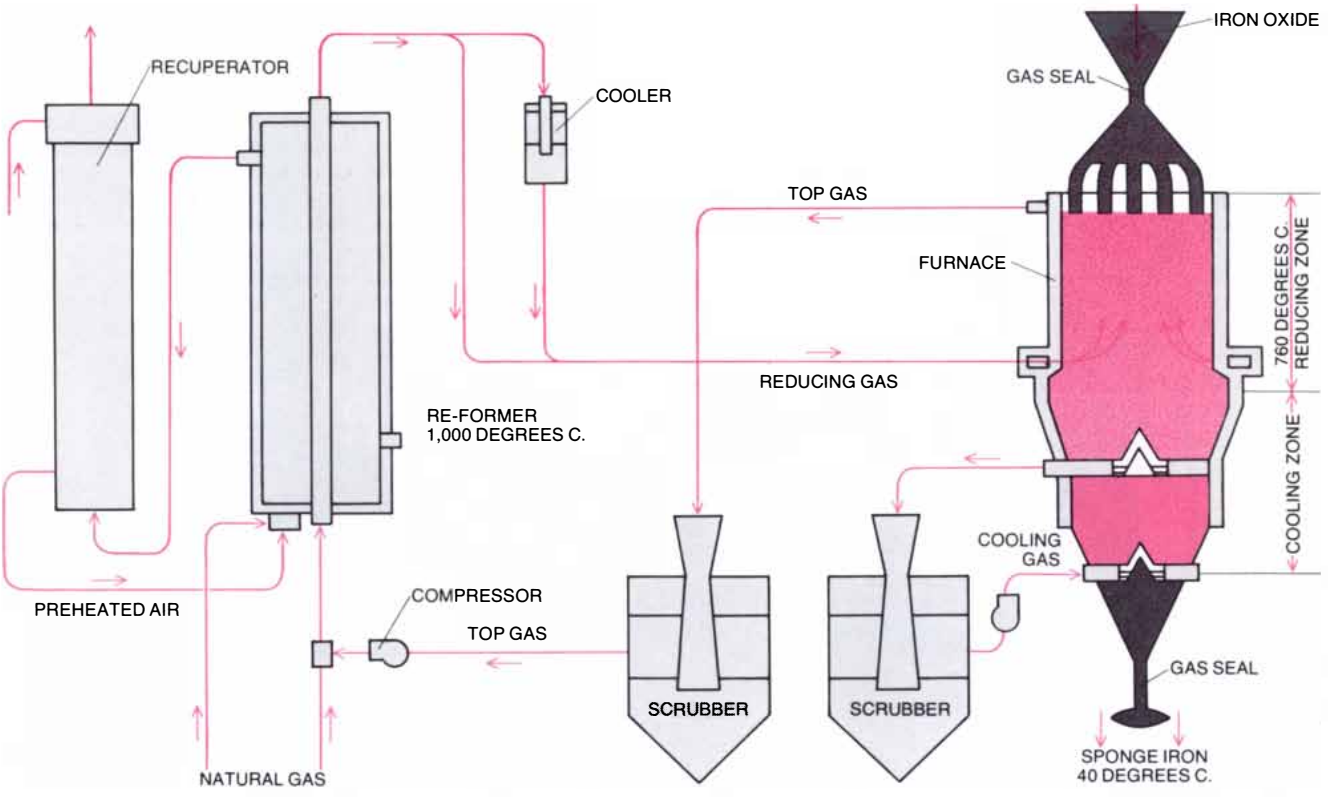
The reduction of iron oxide with solid carbon involves two reactions that usually proceed simultaneously: $Fe_2O_3 + 3C \rightarrow 2Fe + 3CO$ and $Fe_2O_3 + 1.5C \rightarrow 2Fe + 1.5CO_2$. Both reactions are endothermic, that is, they absorb heat. The one that goes to carbon monoxide requires twice as much coal as the other (3C compared with 1.5C), which produces carbon dioxide. The latter reaction is therefore favored for direct reduction with solid reductants. Because equilibrium conditions limit the amount of carbon dioxide in a mixture of carbon dioxide and carbon monoxide, the gaseous products from a direct-reduction process based on coal contain carbon dioxide and carbon monoxide in varying amounts, and the corresponding consumptions of energy differ accordingly.

## Gaseous Reduction

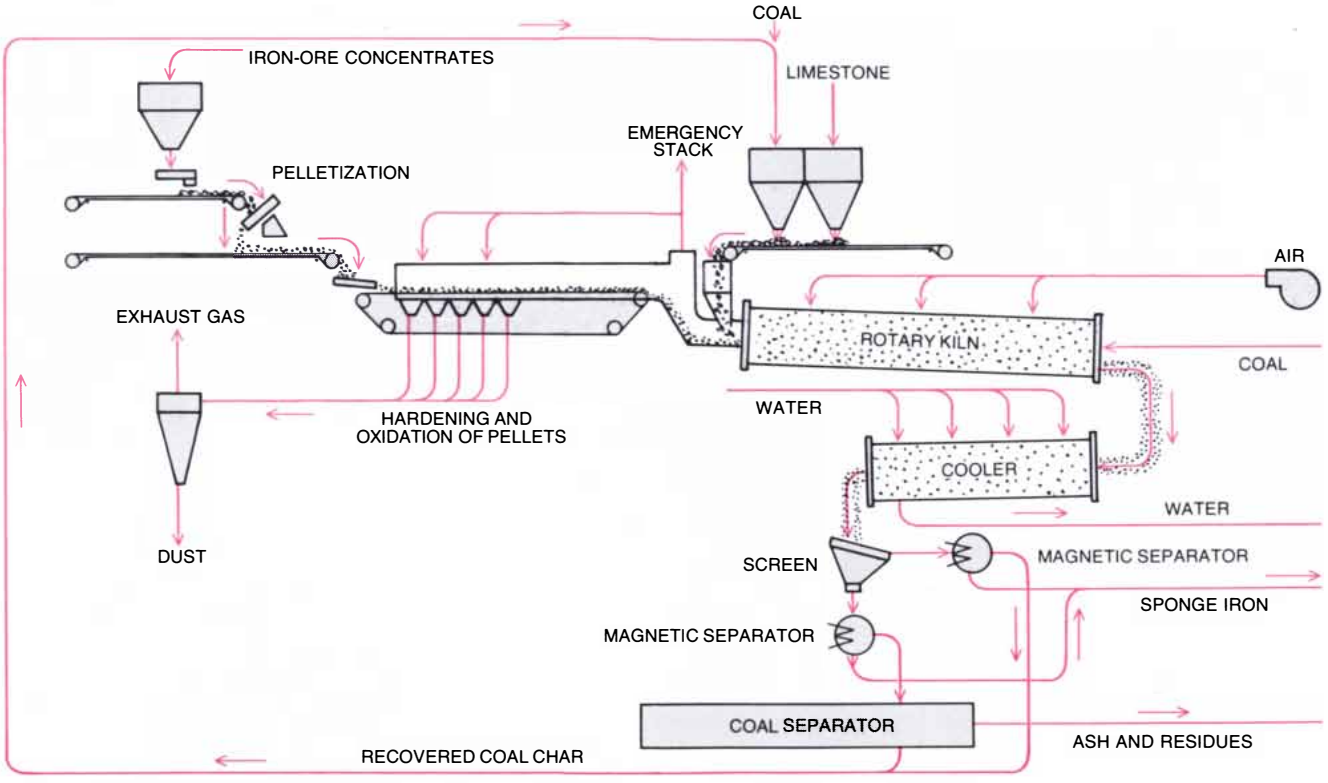
In gaseous reduction the reducing agent is usually a mixture of carbon monoxide and hydrogen. At present such mixtures are obtained mostly by re-forming natural gas in the presence of a catalyst. The major constituent of natural gas is methane ($CH_4$). A common method of producing carbon monoxide and hydrogen is "steam re-forming," in which the reaction is $CH_4 + H_2O \rightarrow CO + 3H_2$. Another method of making the reducing gases is the "water-gas reaction" between coal and steam: $C + H_2O \rightarrow CO + H_2$. In recent years many studies have been made with the objective of obtaining reducing gas for direct reduction by gasifying oil. There is also a great deal of interest in using "waste" gas from coke ovens, blast furnaces and electric smelters producing pig iron; each type of gas has a high caloric value and is excellent for reducing iron.

The time needed for a high degree of reduction declines as the concentration of hydrogen in a reducing mixture is lowered. For economic reasons re-formed gas containing from 75 to 85 percent carbon monoxide is preferred in the present practice of direct reduction. In theory a reduction of 95 percent should be achieved in about an hour with such a mixture, but in fact it takes from three to four hours in the plants now operating. It would seem that opportunities exist for improving the present processes.

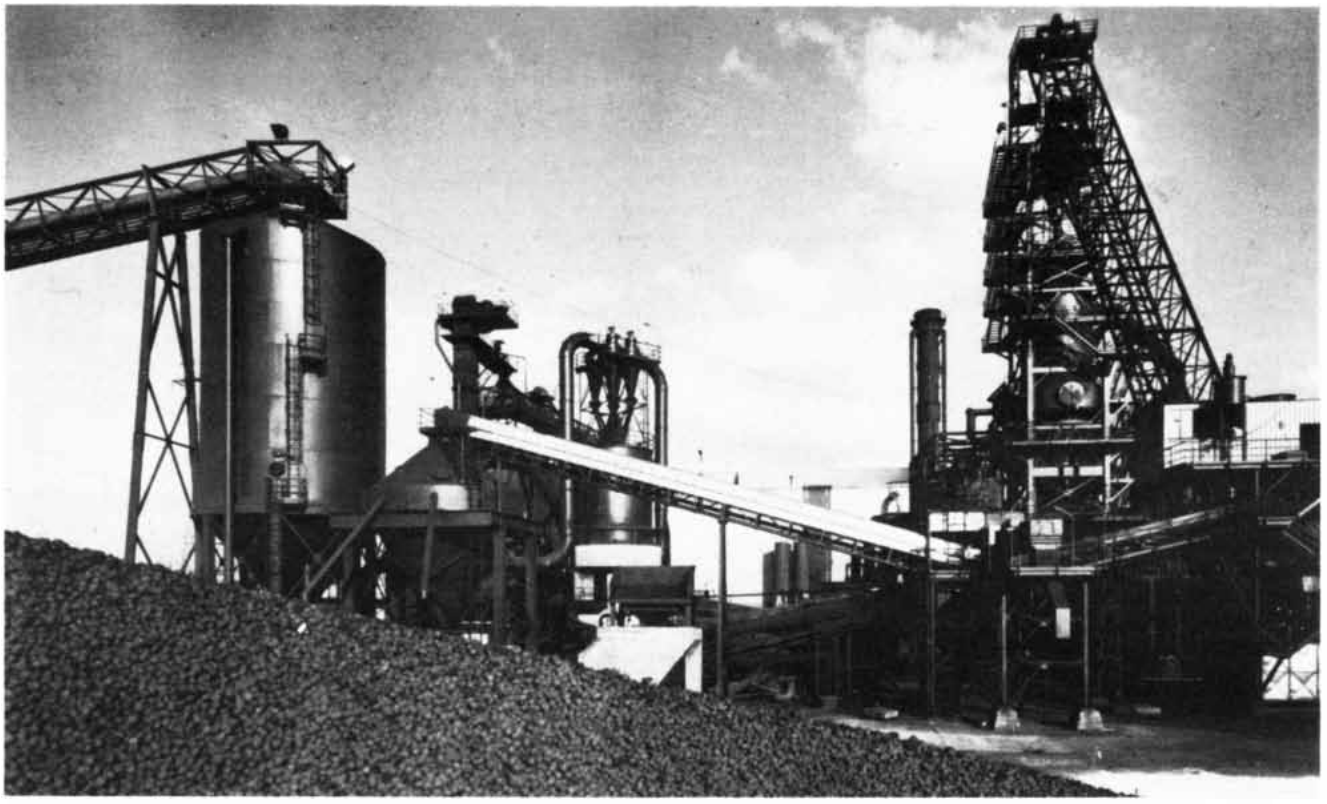
An iron ore that would be ideal for direct reduction would have a high content of iron (more than 60 percent), a low content of impurities and a small amount of gangue (4



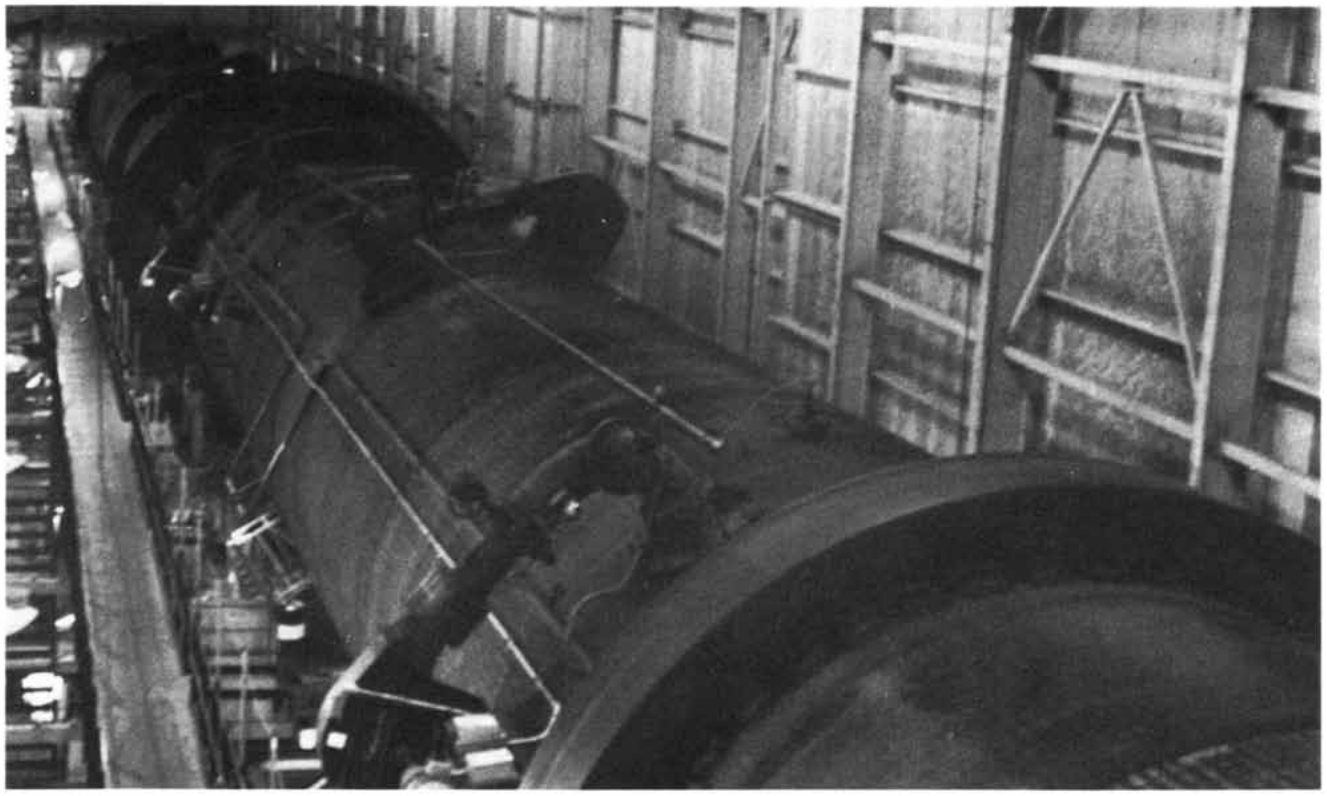

**MIDREX PROCESS** employs re-formed natural gas as the reductant. The process was named by the Midland-Ross Corporation, which developed it. The reducing gas is made in the re-former from a mixture of natural gas and unused gas recovered from the reducing furnace. The furnace is a vertical shaft. A charge of iron pellets and lump ore is loaded into the top of the furnace and descends by gravity through the reducing gas, which is introduced to the stack at about mid-height. Reduction takes place in the upper part of the furnace at a temperature of about 760 degrees Celsius. The reduced sponge iron is then cooled in the lower part of the furnace to about 40 degrees C.




**SOLID REDUCTANT** is the distinguishing feature of the SL/RN direct-reduction process, which derives its name from the first letter of the name of each of four companies that helped to develop it. The reductant is coal, which consists mainly of carbon that reacts with the oxides in the iron ore. A mixture of ore, coal and limestone is fed into a sloping rotary kiln, through which it passes by gravity. A series of burners along the kiln maintain a temperature profile such that the charge of ore, which travels about 100 meters through the kiln, is reduced in from three to five hours. Reduced iron is separated from coal char, which is recycled to the kiln to provide an excess of reductant.



**MIDREX PLANT is operated in Hamburg, West Germany, by Korf Industries, Inc. It has a capacity of 350,000 tons of sponge iron per year. At right is the reducing stack, which has a skip-car charging system. The tall silo at left is a "day bin" in which iron ore and pellets are stored before being transferred by the dark conveyor at center to the skip car that carries the material to the top of the stack. The light colored conveyor at center carries unacceptable processed sponge iron to the "remet" bin, from which it is recycled back to the charging system to be remetallized. In the foreground is part of a pellet-storage yard. Pellets are carried to the day bin by the conveyor at upper left.**

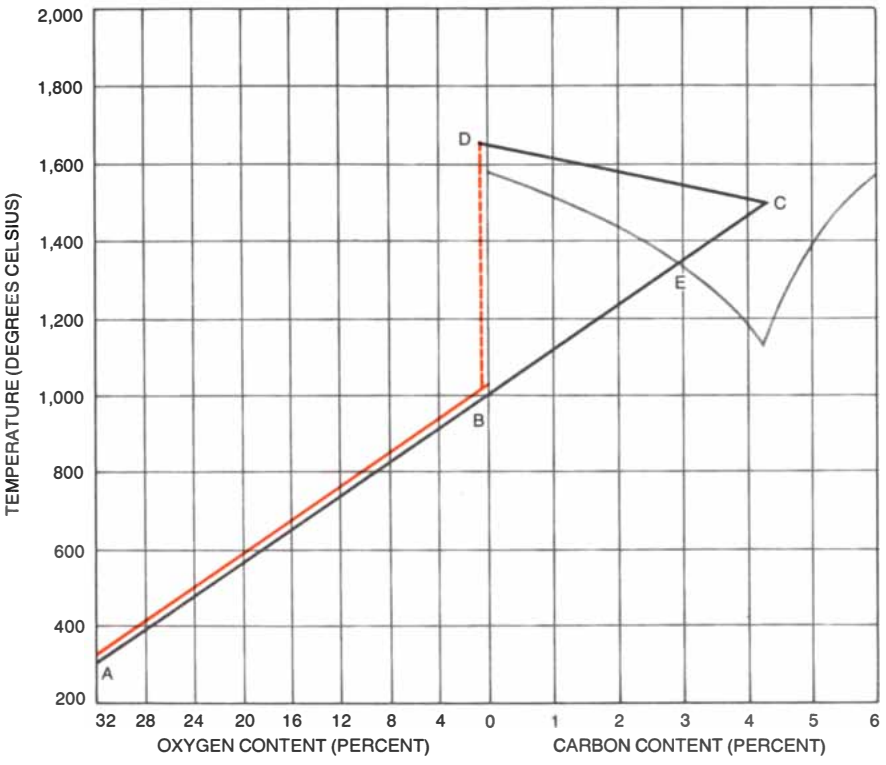


**ROTARY KILN for the direct reduction of iron ore with a solid reductant is operated by the Steel Company of Canada, Ltd., in association with its own mine. Oxide pellets made from the iron ore magnetite serve as the raw material. The pipes that enter the kiln at intervals are part of the system of burners that is employed to heat the charge of ore, coal and limestone as it is moved along sloping rotary kiln by gravity.**

percent or less). It would be easily reducible by gaseous and solid reductants, moderately self-agglomerating, nonswelling and readily made into pellets. As a natural ore and as a pellet it would have an outer surface porous enough for good penetration of gas and firm enough to resist abrasion; its inner structure would be open enough for gas to diffuse easily in it, and it would be strong enough to withstand the mechanical and thermal shocks of processing during prereduction and the pressure and wear that would occur as it was handled in bulk.

Such an ideal iron ore almost certainly does not exist. Nevertheless, substantial tonnages of ore with most of these virtues are available, some of them in their natural run-of-the-mine condition and many more after beneficiation. Contrary to a misconception that is more widespread than it should be, direct reduction will not work with "any" ore.

Nor will "any" coal serve as a solid reductant in direct reduction. Rates of reaction vary widely for different forms of carbon at a given temperature. Reactivity, which is the rate at which a carbonaceous material will reduce iron oxides, is often more significant than the reducibility of the iron ore in a direct-reduction process employing solid carbon. The content of sulfur, phosphorus and volatile matter in the coal is also a consideration. A particularly troublesome contaminant is ash, not only the amount of it but also its composition and the temperature at which it fuses. Coal that is poor in this respect tends to form pasty masses and, more frequently, to build up glassy ring formations on the inner walls of a rotating-kiln furnace. It becomes necessary to reduce the rate of production and even to shut down the entire operation, often for a period of several weeks, in order to remove such accretions.




**PAIRED DIAGRAMS show the changing content of oxygen and carbon in iron ore as the temperature is raised in a furnace. The black line represents the conventional, indirect process of reduction and the colored line represents direct reduction. Ores such as hematite and magnetite, starting (*A*) with a content of about 30 percent oxygen, are reduced (*B*) as the temperature is raised. In the conventional process they are also melted (*C*), and the resulting metal contains from 4 to 5 percent carbon absorbed from the coke that sustained the reduction reactions. In the direct process the iron ore reaches the reduction point (*B*) well below the temperature (*E*) at which iron melts. The reduced iron may then be caused to melt (*D*) in an electric steelmaking furnace so that the content of carbon can be adjusted precisely and impurities can be removed.**

## The Major Processes

By the end of this year 41 direct-reduction plants will be in operation or in various stages of start-up. They represent 12 different designs. A majority of the plants (25) involve gaseous reduction, but 21 of them are accounted for by only two processes: HyL (for Hojalata y Lamina, a steel company in Mexico that developed the process) and Midrex (for the Midland-Ross Corporation, a U.S. firm that introduced the process). The 16 solid-reductant projects include 15 with rotary kilns, of which 11 are SL/RN plants (so designated from the first letter in the name of each of four companies that took part in developing the process) or plants involving modifications of the process. The remaining installations are mostly designed by a number of major steel producers and suppliers of equipment.

The HyL and Midrex processes have gained by far the widest acceptance, mainly because each of them is represented by at least two plants that have reached a commercial level of operation within from three to six months after start-up. Each process employs a gaseous reductant produced from re-formed natural gas that flows countercurrently through iron ore in a cylindrical retort. Processes developed by the Armco Steel Corporation and August Thyssen-Hütte A.G. are based on the same principle. The first HyL plant was put into commercial operation in Mexico in 1957; the first Midrex unit began operating in Portland, Ore., in 1969; Armco opened a plant in Houston in 1973, and a Thyssen Purofer installation was started up in Brazil early this year.

The HyL process achieves the direct reduction of iron ore in four reactors, each containing ore in a stationary bed [*see illustration on pages 70 and 71*]. The reactors operate independently, each one processing ore in a cycle of four steps: preheating, reduction, cooling and unloading. The reactors share a common stream of gas that moves in a closed circuit.

In the first step the raw ore is preheated by recirculated spent gas. The ore is then reduced to sponge iron by fresh gas from the cooling stage. Next the sponge iron is cooled by fresh gas from the re-former; during this stage the reduction is completed. Finally the reduced product is removed from the bottom of the reactor and a new charge of ore is loaded at the top. Each stage takes approximately three hours, so that the completion of a full cycle requires about 12 hours. At any given time each of the reactors is in one of the four steps of the cycle, and so the flow of materials through the plant is virtually continuous.

The reduced product of an HyL system is from 83 to 90 percent metallized. Its carbon content is from 1.5 to 2.2 percent, having been held within that range by carefully controlled cooling. The cooling also stabilizes the iron, preventing it from becoming rapidly reoxidized when it is exposed to the air on being removed from the reactor.

## Other Gaseous Processes

The Midrex process yields a product that is from 92 to 95 percent metallized. A mixture of iron ore and pellets is fed into a vertical-shaft furnace [*see top illustration on page 75*]. Re-formed gas, piped into the stack at about mid-height, rises through the charge of ore and pellets, which is descending. Reduction takes place at a temperature of about 760 degrees C. in the upper part of the furnace, and the reduced sponge iron is cooled in the lower section.

The reducing gas is generated in the reformer from a mixture of natural gas and partially used "off" gas recovered from the top of the metallizing furnace. The lump ore and pellets charged into the stack contain

from 65 to 69 percent iron and ideally are from nine to 16 millimeters in size. It is desirable that the range of sizes be as narrow as possible and that fines and broken pellets be avoided.

The carbon content of the reduced product is from .7 to 2 percent. Gangue is as low as 1.7 percent for pellets from Sweden and as high as 7 percent for ores from Canada. The process achieves a metallization of 95 percent in about six hours. Reoxidation of the reduced product is limited by a passivating treatment that consists in applying a coating that forms a thin layer of oxide on the surface of the sponge iron. Reduced iron thus protected has been shipped more than 6,000 miles by sea with reoxidation losses of less than 5 percent, which is an acceptable level.

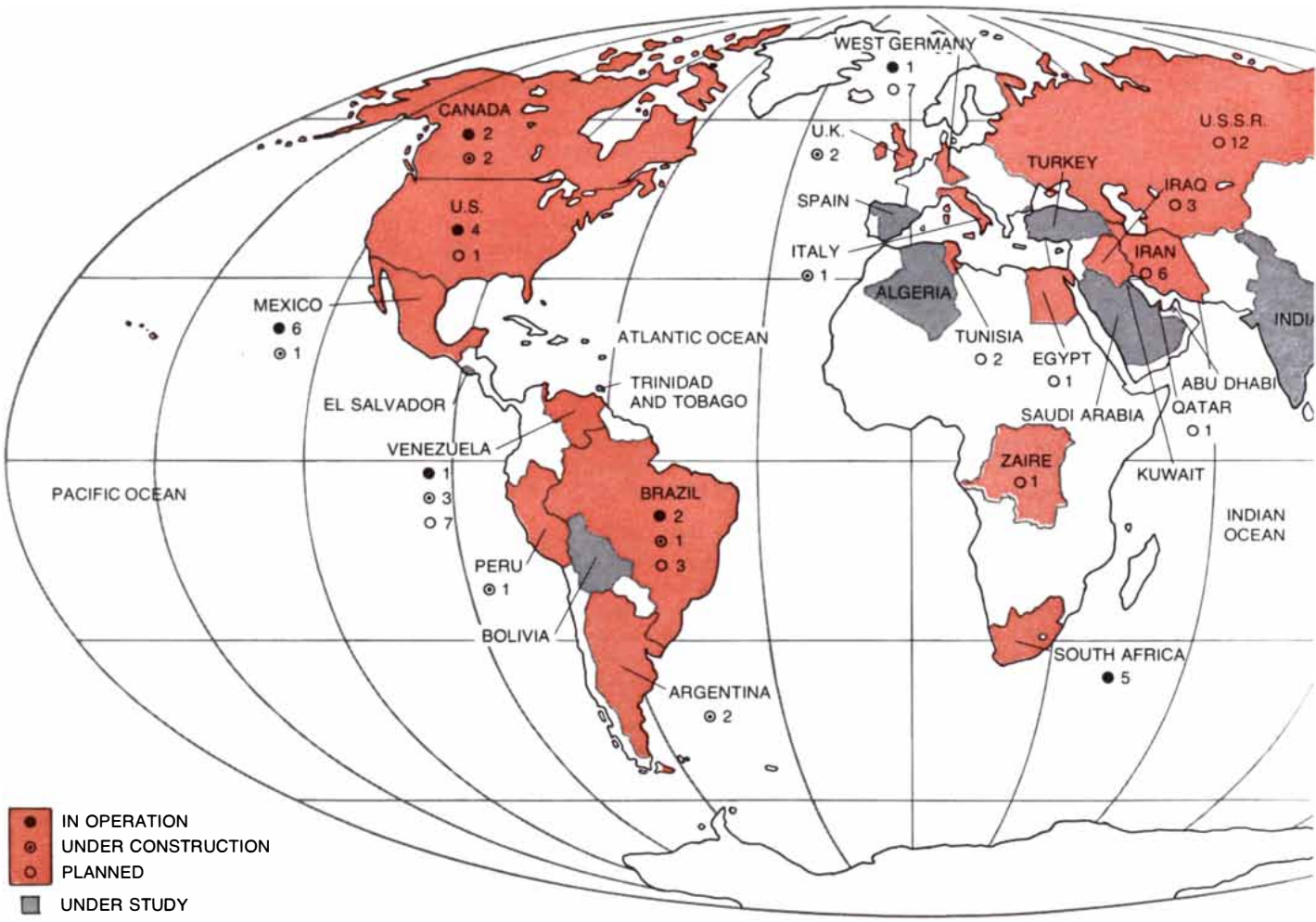
Armco and Purofer plants are much like the Midrex process in design and operating principles. Both processes entail a countercurrent flow of iron ore and re-formed gas in a vertical shaft. The feeds of ore are comparable, the degree of metallization is the same (95 percent), the energy requirements are of the same magnitude and the temperatures of reduction are similar (900 degrees C. for Armco and 1,000 for Purofer). Armco sponge iron, like the product of the HyL and Midrex processes, emerges in the form of lumps about half an inch in size; the product of the Purofer process is a briquette that does not reoxidize readily because of its small surface area.

Two other gaseous reduction processes employ fluidized-bed techniques: the HIB (for high-iron briquette) process, developed by the United States Steel Corporation, and the FIOR (for fluidized iron ore reduction) process, developed by the Exxon Company and engineered and promoted by Arthur G. McKee & Company. Reducing reactions between iron ore and re-formed natural gas are achieved as fine ore solids flow like liquids during the upward passage of the gas under controlled conditions of temperature and velocity [see "Fluidization," by H. William Flood and Bernard S. Lee; SCIENTIFIC AMERICAN, July, 1968]. Installations of both types have been built in Venezuela to process domestic ore fines into briquettes of reduced iron. The FIOR product is from 88 to 93 percent metallized; the HIB briquette, which is produced primarily as a feed for furnaces making iron rather than as a feed for electric furnaces making steel, is held at a metallization of from 70 to 75 percent. The content of carbon is 2 percent or less in the FIOR product and about 1 percent in the HIB briquette.

In the fluidized bed the fine particles of ore are in close contact with the reducing gas. The close contact is conducive to good rates of heat transfer and chemical reaction, but it gives rise to a higher requirement for energy than is characteristic of the other gaseous reduction processes.

The air pollution resulting from the gas used in a gaseous direct-reduction plant can be held at an acceptably low level by the installation of carefully designed closed gas systems. The emission of particulates is reduced by the liberal use of filters in the water circuits and dust collectors at the places where reactors and storage bins are loaded and unloaded. Engineers associated with the Purofer process have asserted that the combination of direct reduction of iron ore with steelmaking in an electric furnace diminishes atmospheric contamination by half and that the volume of noise is about a fifth of the level usually reached at an installation combining a blast furnace and a basic-oxygen converter.

Although the experiments in direct reduction done by Siemens a century ago




**EXTENT OF DIRECT REDUCTION is shown by this map on which the countries that have direct-reduction plants or are building or planning them are shown in color. The plants that were in operation at the end of 1975 had a total capacity of six million tons of sponge iron per year. The capacity of the plants being built now and scheduled to begin operating by the end of this year will be 6.4 million tons per year.**

made use of a rotating furnace, the present installations with rotary kilns (and coal as the reducing agent) grew out of processes developed in Germany between 1925 and 1935. I have mentioned the SL/RN process; there are in addition a Krupp process, which is almost the same as the SL/RN system, and several modifications that embody similar principles. Among all the methods of solid reduction the SL/RN process has received by far the most attention.

## Solid-Reductant Processes

The SL/RN system combines the ideas of two designs introduced about 20 years ago. One design was the original SL process, which included a rotating cylinder that was tilted slightly from the horizontal position so that the ore and the reducing coal fed into one end would move by gravity through several heating zones and would emerge from the other end. The other was the RN refinement, which added a system of burners along the length of the cylinder. The input of fuel to the burners can be controlled so that any temperature profile can be maintained inside the kiln. A typical kiln in the SL/RN system is about 100 meters long and from three to five meters in diameter.

Ore is charged into the kiln as small particles from the mine or as fine agglomerates. Reducing agents come in a wide range of solid carbonaceous materials; it is preferable that such a material have a low sulfur content and a high ash-fusion temperature. Limestone and dolomite can be included in the charge to lower the sulfur content. Supplementary heating fuels such as natural gas, "waste" gas and fuel oil are often used.

The mixture of iron ore and crushed coal is heated to about 1,100 degrees C. as it passes through the kiln. The trip takes from three to five hours. To reduce the loss of heat the carbon monoxide rising from the bed of ore is often burned in the kiln. After the mixture has been discharged from the kiln and cooled the iron-bearing product is separated from the other materials, such as coal char, by screening. The char is recycled so that the kiln always contains an excess of reducing agent. The sponge iron is from 92 to 95 percent metallized.

The acceptance of coal-based kiln processes for direct reduction has been rather slow. Mechanical and operating problems have been difficult to solve, so that some installations have been delayed in reaching a commercial level of operation. The sponsors of kiln systems have persevered, however, and last year reports of improved results came from plants in New Zealand, South Africa, Japan and Brazil. Two SL/RN plants began operating last year; one of them, the largest facility yet erected for direct reduction with coal, is at an iron mine in Canada and has a capacity of 400,000 tons of sponge iron per year, and the other, with a capacity of 60,000 tons per year, is in Arizona.

Two new processes are being introduced this year in plants of commercial size. The Allis-Chalmers kiln at Sudbury in Canada employs a fuel-injection system and combustion that passes through the charged materials on the bottom of the rotating kiln. The facility can use light and heavy oil as well as mixtures of oil and coal for reduction. The other plant embodies the Kinglor-Metor (KM) process, which is the only solid-carbon system that does not include a kiln. A charge of iron ore, coal and flux moves downward through preheating and reducing zones of a vertical shaft that is heated externally. Sponge iron, from 85 to 95 percent metallized, is produced in modular units that have a capacity of about 20,000 tons per year. A plant with two such modules is scheduled to begin operating soon near Milan.

In 1970 the production and consumption of directly reduced iron for steelmaking was slightly more than a million tons. The capacity of the direct-reduction plants scheduled to be in operation by 1980 will be more than 30 million tons. The spread of direct reduction has been particularly rapid during the past decade. In 1965 the only direct reduction on a commercial scale was done by two plants in Mexico with a rated capacity of 350,000 tons of sponge iron per year; at the end of 1975 there were 25 plants in nine countries with a total rated capacity of six million tons. An important contribution to this trend was the demonstration in 1973 that HyL and Midrex technologies can be transferred, that is, that experience gained at existing plants can be adapted quickly at new installations so that a high level of operation can be reached in a few months after start-up.

## Direct Reduction and World Steel

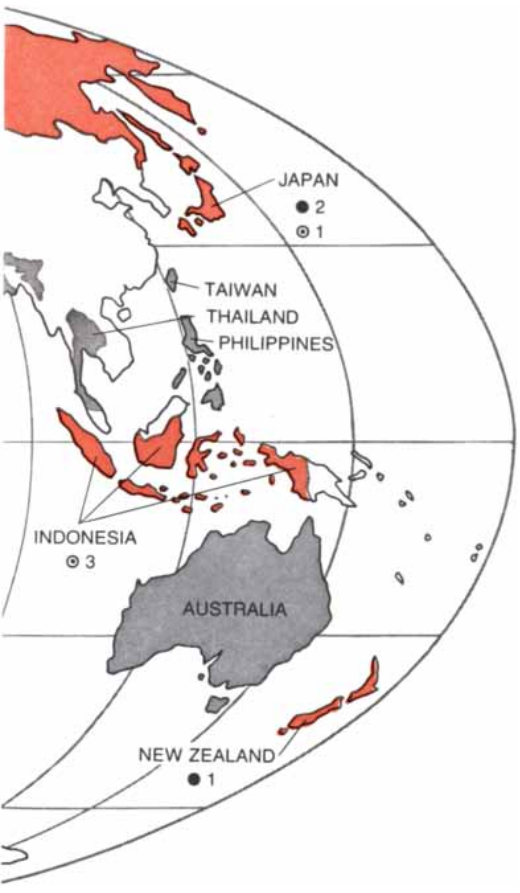
In 1969 I published a prediction that the production of sponge iron will be some 60 million tons by 1980 and 120 million tons or more by 1985. Increases of this order will have to be made if the industry is to achieve the growth that has been forecast for it. The worldwide production and consumption of steel is expected to be a billion tons per year before 1985. Direct reduction will be needed to complement the established techniques of steelmaking if such tonnages are to be reached.

My forecasts for the production and consumption of raw steel on a worldwide basis are 915 million tons in 1980 and 1,025 million tons in 1985. I foresee a demand for 64 million tons of sponge iron in 1980, including 42 million tons for steelmaking and 22 million tons for the production of iron. By 1980 the total should be 124 million tons, including 88 million tons for steel and 36 million tons for iron. If direct reduction reaches these levels of output, the production of pig iron by blast furnaces and the corresponding demand for coke would be reduced by 13.5 percent in 1980 and by almost 22 percent in 1985. The use of directly reduced iron would also relieve a tight situation in the world supply of scrap, a condition that is likely to become chronic after 1980.

The more than 30 million tons of direct-reduction capacity already scheduled for operation by 1980 is intended almost exclusively for the production of materials to charge electric furnaces that make steel. Prereduced iron in small lump and pellet sizes is also well suited as a replacement for scrap in basic-oxygen furnaces, however, and as greater amounts of sponge iron become available and scrap supplies become more limited, increased quantities of directly reduced materials will be consumed in such furnaces.

The use of sponge iron for conventional ironmaking will also increase as the cost of building blast furnaces rises and the availability of coking coal declines. Tests have established that the addition of prereduced iron to the burden of a blast furnace improves ironmaking. Whenever the metallization of the charge in the furnace is increased by 1 percent, the iron output of the furnace rises by .7 percent and its consumption of coke declines by .5 percent.

Most of these broadened demands for directly reduced iron had been foreseen before 1975, but they have been expanded immeasurably by a development that took




**Plants on firm order to begin operation before 1981 will have a capacity of 18.3 million tons, plants that are under study 20.5 million tons.**

place in Venezuela during that year. The site (at Matanzas on the Orinoco River) where Venezuelan engineers planned a major expansion of steel production had, on the one hand, ample quantities of high-grade iron ore, natural gas, electric power and water at favorable prices and, on the other hand, a lack of coking coal and scrap. Under those conditions the combination of direct reduction and electric-furnace steelmaking was judged to be superior to the conventional combination of blast furnaces and basic-oxygen furnaces. In December orders were placed for three HyL and three Midrex plants to produce a total of 3.2 million tons of sponge iron per year.

## A Comparative Analysis

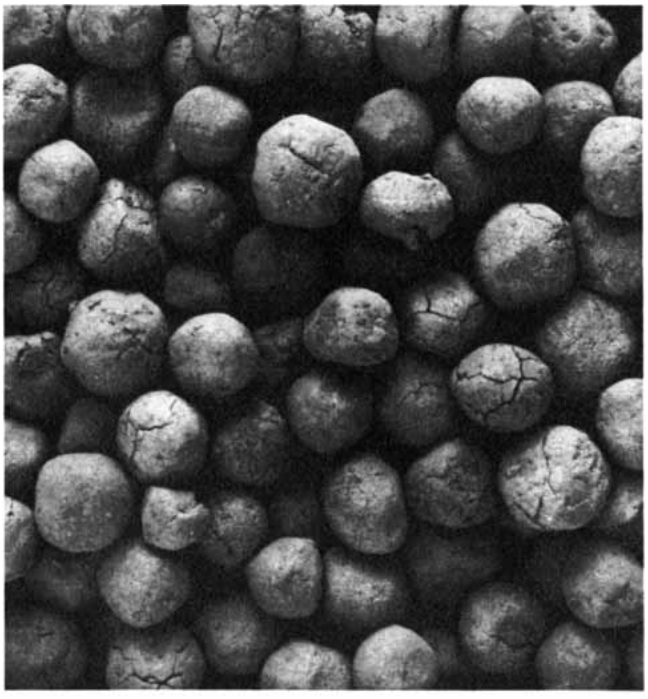
As a member of a World Bank mission working with the Venezuelan planning group, I had participated early in 1975 in an analysis that found, among other things, that the steels made by the combination of direct reduction and the electric furnace are comparable in quality to the steels made by the combination of a blast furnace and a basic-oxygen furnace; that the direct-reduction, electric-furnace method is about 40 percent lower in capital cost and 20 percent lower in production cost than the conventional method, and that the average rate of return on investment is appreciably higher with the direct-reduction method. Later, in a more general evaluation of a facility with a capacity of a million tons of steel billets per year, I found that the estimated capital cost of a plant combining direct reduction with steelmaking in electric furnaces would be 32 percent below the capital cost of a plant combining blast furnaces and basic-oxygen furnaces and 28 percent below the cost of a plant in which electric furnaces would make steel from scrap. Production costs for billets made by the method combining direct reduction and the electric furnace were estimated to be 8 and 23 percent respectively below those for the other two methods, and the direct-reduction combination promised the highest return on investment.

The general analysis showed that the economic viability of each process is sharply responsive to the availability and the price of the raw materials that the process requires. The method combining blast furnaces and basic-oxygen furnaces depends primarily on coke or coking coal, the scrap method on scrap and the direct-reduction, electric-furnace method on reductant fuel. For the first two methods directly reduced iron represents an important option for substitution; in the process combining a blast furnace and a basic-oxygen furnace it is useful in moderate amounts as an addition to the charge of ore in the blast furnace and as a coolant in the basic-oxygen converter, and in the scrap method it can serve in larger amounts as a replacement for steel scrap.

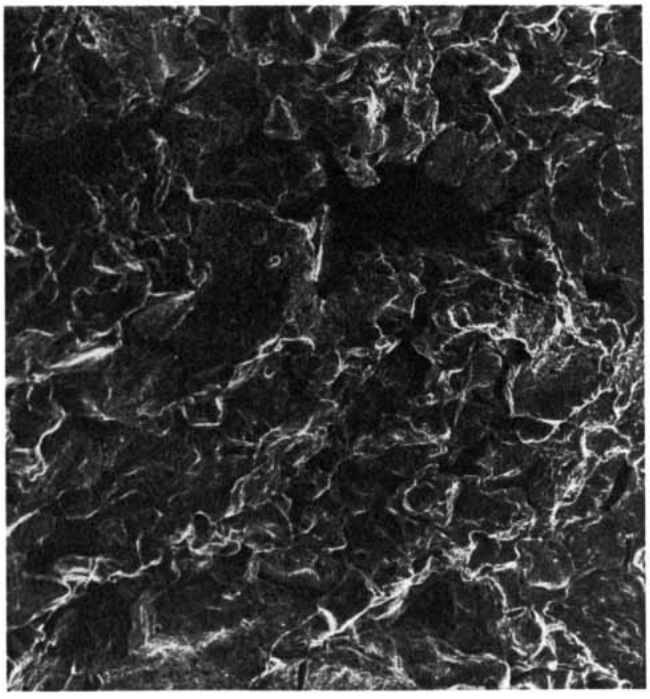
The general study led to the conclusion that the products of a system combining direct reduction and electric furnaces were equal to or better than the products of the conventional method (blast furnaces combined with basic-oxygen furnaces) in quality, control of environmental pollution and flexibility in siting plants. Another finding was that the effect of changes in the cost of fuel is less for a plant combining direct reduction and electric furnaces than it is for the combination of blast furnaces and basic-oxygen furnaces. For the first method the charges for fuel, electricity and electrodes amount to about a fourth of the cost of the steel billets produced, whereas in conventional practice the cost of coke, oxygen and electricity is about a third of the cost of the steel billets.

The general study also found that the gross consumption of energy per ton of liquid steel is comparable for the method combining direct reduction and the electric furnace and the method combining the blast furnace and the basic-oxygen furnace, being respectively about 21,000 and 22,000 megajoules. For all scrap methods the figure is 13,300 megajoules per ton. When the energy content of by-products and "waste" gas is recovered, the net energy consumption in a plant combining blast furnaces and basic-oxygen furnaces is reduced to about 14,000 megajoules per ton of liquid steel. The recovered gas accounts for 70 percent of the change. This potential for recovering energy is the basis for investigations of practices combining blast furnaces and direct-reduction units so that by-product gases from the blast furnace (and also from coke ovens and electric smelters) serve as the reductant in the direct-reduction unit.

The use of nuclear reactors as a source of heat to make supersaturated steam for reforming natural gas would reduce the energy requirement for most direct-reduction processes by about a third. This possibility is under study in several countries, including the U.S., Britain and Japan. It is unlikely that the studies will bear fruit until problems in the design of nuclear reactors have been fully solved, perhaps 20 years from now. By that time the principles of direct reduction may be incorporated in continuous steelmaking processes in which iron ore is injected at one end and steel billets, blooms and slabs emerge automatically at the other end.



**IRON PELLETS manufactured by the Midrex direct-reduction process at Sidbec plant are from two to three centimeters in diameter.**



**SPONGELIKE MICROSTRUCTURE of directly reduced iron appears in this micrograph of a pellet. Enlargement is 600 diameters.**

# JAGUAR UNLEASHES A NEW BREED OF CAT. THE S-TYPE.

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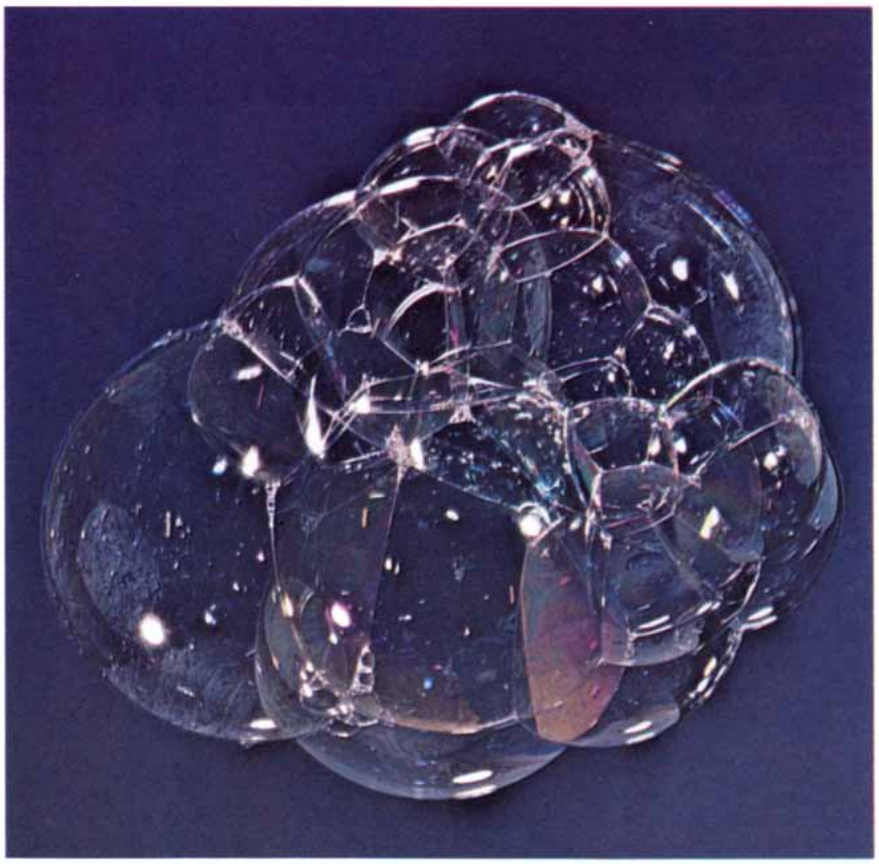
# The Geometry of Soap Films and Soap Bubbles

*The possible configurations they can form are governed by a few elementary rules that have been known for more than a century. A new mathematical model provides a sound basis for those rules*

by Frederick J. Almgren, Jr., and Jean E. Taylor

Soap bubbles and soap films evoke a special fascination. Their shifting iridescence, their response to a puff of air, their fragility—all contribute to their charm. More captivating still is the exquisite perfection of their geometry, the absolute smoothness of their forms. What are the principles that enable soap bubbles and soap films to exist in certain geometric configurations and not in others? What are the possible shapes they can assume?

Three tentative principles are likely to suggest themselves to anyone who looks carefully at a number of different bubbles and films. First, a compound soap bubble or a soap film spanning a wire frame consists of flat or smoothly curved surfaces smoothly joined together. Second, the surfaces meet in only two ways: Either exactly three surfaces meet along a smooth curve or six surfaces (together with four curves) meet at a vertex. Third, when surfaces meet along curves or when curves and surfaces meet at points, they do so at equal angles. In particular, when three surfaces meet along a curve, they do so at angles of 120 degrees with respect to one another, and when four curves meet at a point, they do so at angles of close to 109 degrees.



**FLOATING CLUSTER of soap bubbles is suggestive of the infinite variety of configurations that can be formed by compound soap bubbles or soap films spanning a wire frame. In spite of the apparent complexity of such shapes the separate pieces of flat or smoothly curved surfaces can come together in only two ways. The color photographs accompanying this article were made by Fritz Goro using a homemade bubble solution consisting of roughly equal amounts of water and commercial dishwashing detergent, with a small admixture of glycerin to stabilize the films.**

The first person to have studied the geometry of soap bubbles and soap films systematically and to have recorded these simple general rules governing their possible forms appears to have been the Belgian physicist Joseph A. F. Plateau, who conducted his research more than a century ago. In his honor an entire range of mathematical questions that deal with the geometry of soap-bubble-like and soap-film-like surfaces is referred to as Plateau's problem.

Recently we have been able to show that the three basic rules governing the geometry of soap bubbles and soap films are a mathematical consequence of a simple area-minimizing principle. Other principles of this general type have been studied in connection with soap bubbles and soap films for at least two centuries by many well-known mathematicians but never before with the present simplicity of formulation or with the present success in revealing the true geometric underpinning of Plateau's rules. Here we shall describe both the area-minimizing principle itself and explain some of the mathematics necessary for its use.

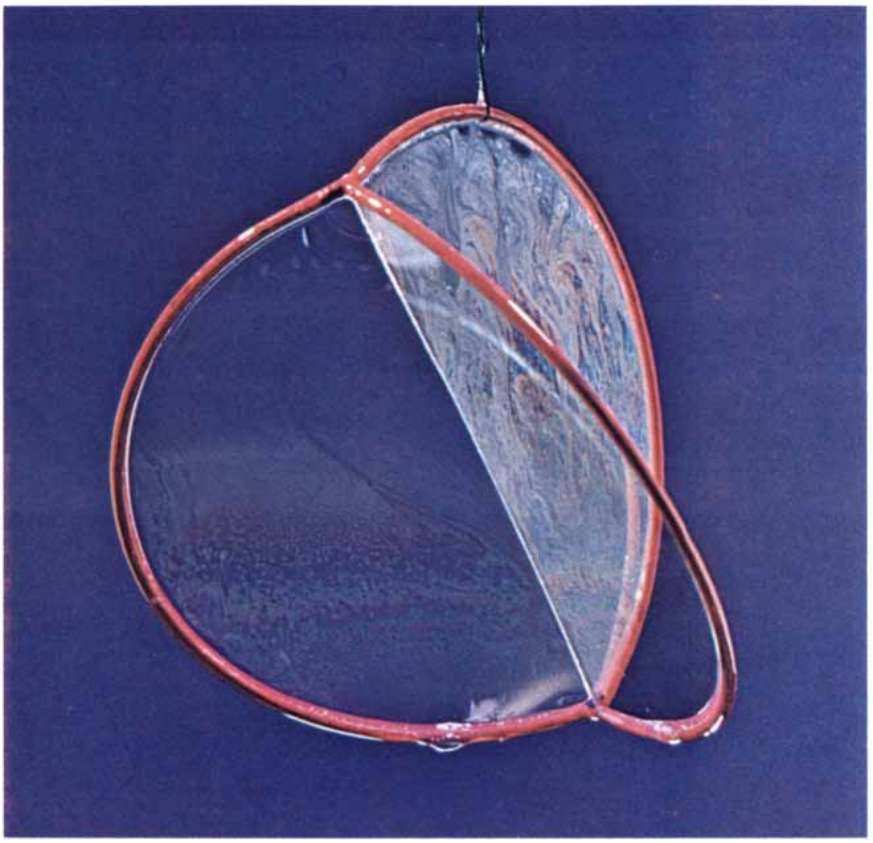
The three basic rules cited above do not completely characterize the geometry of soap bubbles and soap films. Indeed, there are a number of subtler conditions that such configurations must satisfy; for example, it has long been known that the mean curvature of each separate piece of surface must be constant everywhere on that piece. This condition and as far as we know all such conditions are also satisfied by our mathematical model. (In addition Plateau's laws do not explain how a soap film attaches to a wire frame.)

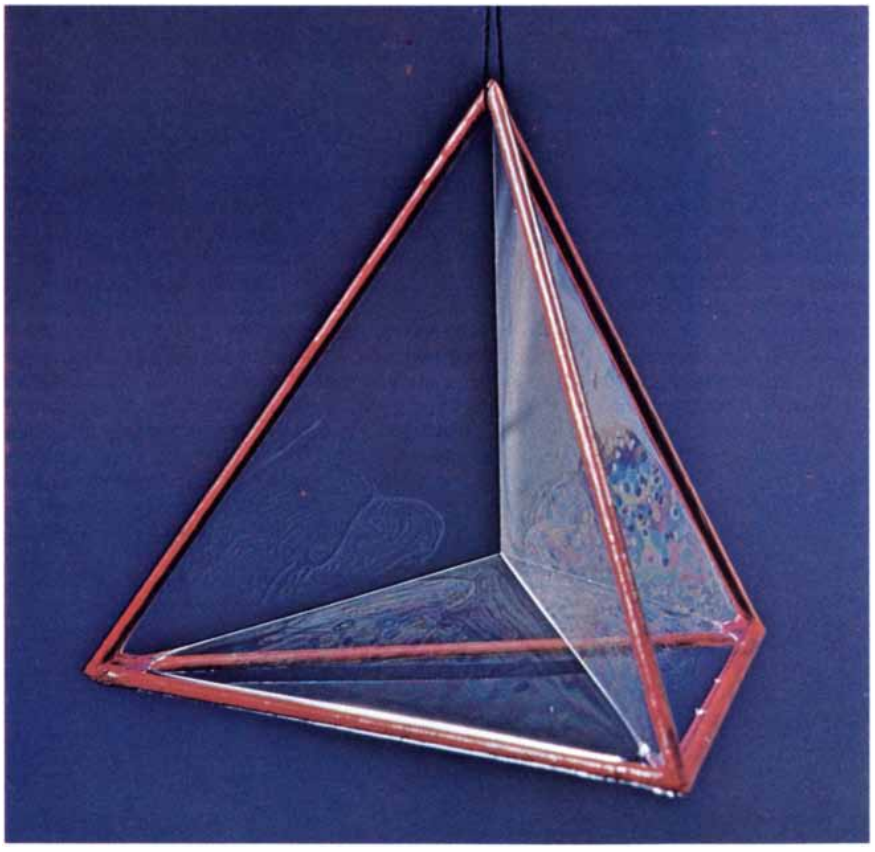
The basic physical principle governing the geometry of soap bubbles and soap films is simply stated: A physical system will remain in a certain configuration only if it cannot readily change to a configuration with less energy. In any liquid at a constant temperature and at rest, whether it is a bulk liquid in a container or a thin layer of liquid in a soap bubble, the relevant components of the energy are the gravitational potential energy, the compressional energy of any volumes of trapped air and the surface energy (often expressed in terms of the surface tension). The surface energy arises as a result of the attractive forces between molecules, which are unbalanced at the surface of the liquid [*see top illustration on page 85*]. The existence of these unbalanced forces means that in the absence of gravity and differences in air pressure the surface of a liquid will act as an elastic membrane, tending to minimize its surface area and thereby its surface energy. These unbalanced forces are much stronger between polar molecules, such as those of water, than between nonpolar molecules, such as those of gasoline. (A polar molecule is one with an asymmetrical distribution of electric charge.)

A soap or detergent molecule is somewhat peculiar, consisting typically of a long, slender nonpolar hydrocarbon chain with a highly polar oxygen-rich group attached at one end. When such molecules are added to water, they tend to migrate to the surface and orient themselves so that their nonpolar ends are sticking out [*see middle illustration on page 85*]. The surface of the water is thus partly or entirely covered with a nonpolar layer that reduces the surface tension drastically. The addition of the soap to the water has two important effects on the formation of a film. First, the surface of the liquid acquires additional stabilizing elastic properties: the stretching of the layer of soap molecules on the surface results not only in an increase of the total surface area but also in an increase in the surface energy per unit surface area (in other words, the surface tension), owing to the decrease in the number of soap molecules per unit area. The effect is attributable to the fact that the new surface created by stretching must be made up of the water molecules that were just below the surface until other soap molecules can diffuse to the surface; it may not take long for this process to happen, but the time involved is adequate to provide a critically important restoring force for small perturbations.

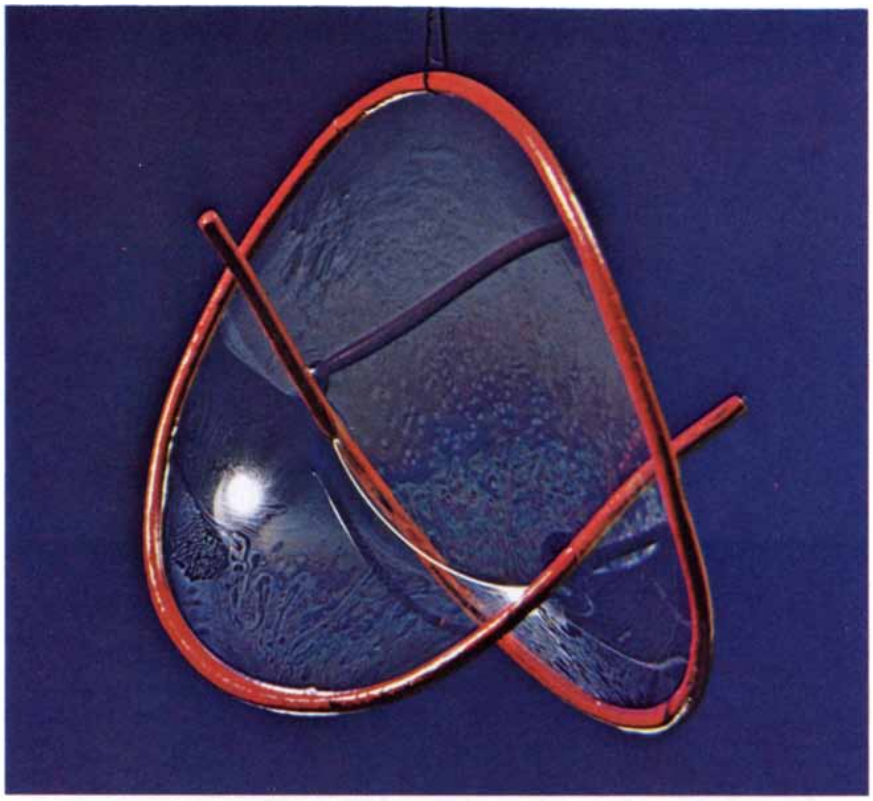
The second effect of soap on the formation of a film is that it seems to limit the minimum thickness of soap films to the length of two soap molecules stacked end to end, one for each side of the film [*see bottom illustration on page 85*]. Moderately thick films can be shown mathematically to be self-healing with respect to small punctures, but this healing ability diminishes greatly as the films become thinner. Hence without something to limit the thinness of the films, they probably could not form.

The actual formation of a soap film as a simple wire frame is lifted from a bowl





**THE TWO WAYS soap bubbles or soap films can meet are demonstrated here with the aid of flat soap films formed on wire frames. The photograph at top shows three flat surfaces meeting along a straight line segment at angles of 120 degrees. The photograph at bottom shows six flat surfaces meeting three at a time along four straight line segments that in turn meet at a vertex at angles of about 109 degrees. It has long been observed and has now been proved mathematically that branchings of these two types (and their curved versions) are the only possible ones.**



**UNUSUAL SOAP FILM forms on a comparatively thick wire frame that has two free ends, even though such a film does not "span" a topologically defined hole. No mathematical soap-film-like configuration can form on a similar, infinitely thin frame that has two free ends. The authors' model of soap-film-like surfaces holds for both thick frames and infinitely thin ones.**

**"FRAME" for soap-bubble-like and soap-film-like configurations need not resemble wire at all. For example, the tabletop seen in this view serves as a frame for an array of fallen bubbles.**

of soapy water is easy to observe, and the elastic nature of the surface is quite apparent. As the wire begins to lift from the water, it raises the elastic skin of the soapy water. The force of gravity acting on the water causes the water to drain from inside the raised surface, making the surface begin to collapse on itself, thus forming a multilayered film. The process continues until as the wire leaves the water the surface pinches off at the bottom, leaving the wire free and carrying a soap film.

The situation is roughly analogous to what would happen if one had a wire frame inside a tightly stretched balloon filled with water and slowly extracted the water from inside the balloon by a straw through the neck [*see illustration on page 86*]. On a wire frame consisting of three half-circles joined together at their ends and lying in planes at angles of 120 degrees with respect to one another, the balloon would collapse to a shape resembling three half-disks joined at angles of 120 degrees along their diameters. After a while extracting the water, say by sucking on the straw, actually has the effect of increasing the surface area of the balloon. Similarly, in the formation of a soap film on the same wire frame the gravitational force on the water inside the elastic skin is necessary in order to achieve the increase in surface area that accompanies the formation of the film.

Once a soap film has formed, either as a soap bubble or within a wire frame or as a combination of both, it will be in an equilibrium configuration only when it cannot readily change to a configuration with less energy. What changes of this type are possible? The film at this point has so little mass that the effect of gravitational potential energy on the geometry of the film is negligible, and the surface energy and the compressional energy of any trapped volumes of air predominate.

First of all, it must be noted that changes of configuration due to breaking or separation of the film from a wire frame do not happen readily, even though they would considerably decrease the surface area. Such events require intermediate changes in the configuration of the multilayered film, and these changes do not take place easily for largely molecular reasons.

One way soap films can change is often seen when two soap bubbles are brought together. Each bubble retains its own spherical shape until the instant the bubbles touch. Once they touch they may form a totally different configuration. Instead of having the four separate surfaces the bubbles would have had if they had been pressed together without joining, the films flow together. That eliminates part of the outer surface of each bubble and thereby substantially decreases the total surface area and the total surface energy of the original configuration.

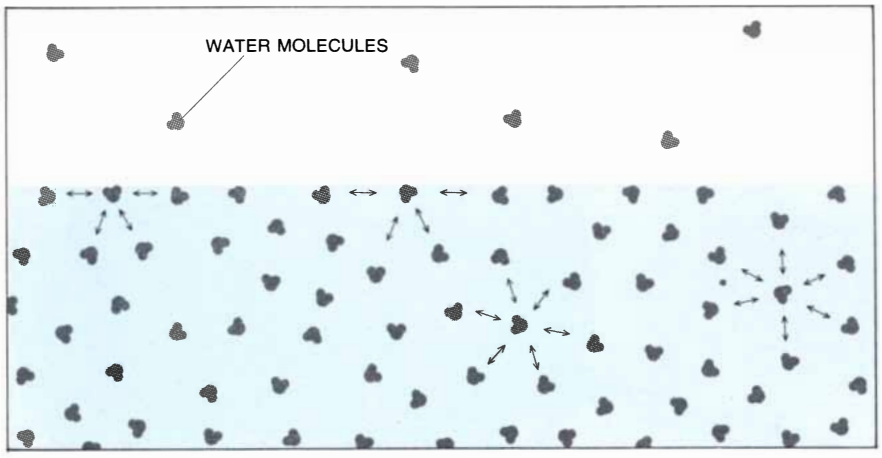
A second method by which soap films decrease their total exposed surface area also involves changes in configuration. For example, under very unusual circumstances

(such as rather viscous soapy water and very closely spaced wires) four pieces of surface can apparently meet along a curve. This seems to happen only when an unusually large amount of water is trapped along the curve where the four surfaces meet, and in such a situation the physical model of a soap film as two very closely spaced surfaces with only a little water between them is no longer applicable. Under normal circumstances a soap film will invariably decrease its surface area by changing configuration whenever more than three pieces of surface meet along a curve or whenever the angles of meeting are other than equal.

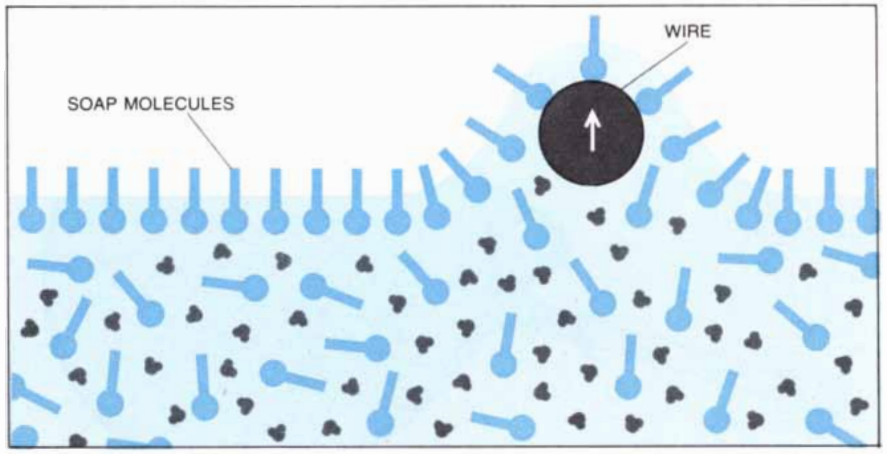
How does one go about constructing a mathematical model of soap bubbles and soap films that will faithfully represent the essential geometric features of the physical model? As a first step in our analysis we approximate the three-dimensional multilayered physical soap film with pieces of two-dimensional surfaces. We then say that a geometric configuration of two-dimensional surfaces attached to a frame is soap-film-like if it cannot be made to have a smaller area by any small deformation that leaves the frame fixed. In case a deformation causes two or more pieces of the surface to coincide, we count the areas where the surfaces overlap only once, thereby mimicking mathematically the manner in which actual soap films join. (In the past most mathematical models of area-minimizing surfaces have required that the areas of overlapping surfaces be counted more than once.)

In making a mathematical model for soap bubbles or soap films that include bubbles one must take into account the energy associated with the regions of trapped air. There are several different reasonable ways in which this could be done. Since they all lead to essentially the same result, we select the simplest: we permit no changes in the net volume of each trapped region of air by the deformations we allow. With this in mind, we say that a geometric configuration of two-dimensional surfaces is soap-bubble-like provided that it encloses one or more regions of space and that it cannot be made to have a smaller area by any small deformation that leaves the net volume of each enclosed region fixed; if a frame is involved, we again require that the deformations leave it fixed. The area of the deformed surfaces is measured in the same manner as it is for the deformations of the soap-film-like surfaces.

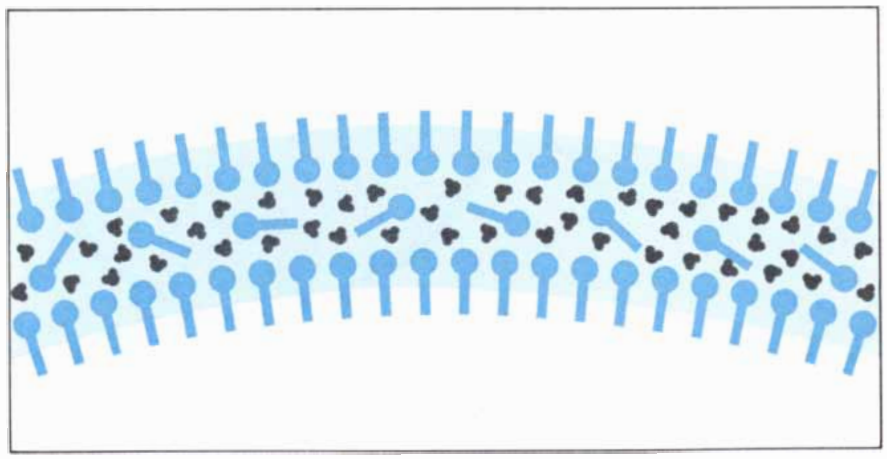
We are now in a position to ask mathematical questions about our mathematical model. Suppose, for example, one is given a frame. Are there any soap-film-like configurations of mathematical surfaces that span this frame? Alternatively, suppose one specifies the volumes of various regions (and perhaps also specifies a frame). Is there any soap-bubble-like configuration of mathematical surfaces that encloses regions of exactly these prescribed volumes (and also spans the frame)? Assuming that one is able



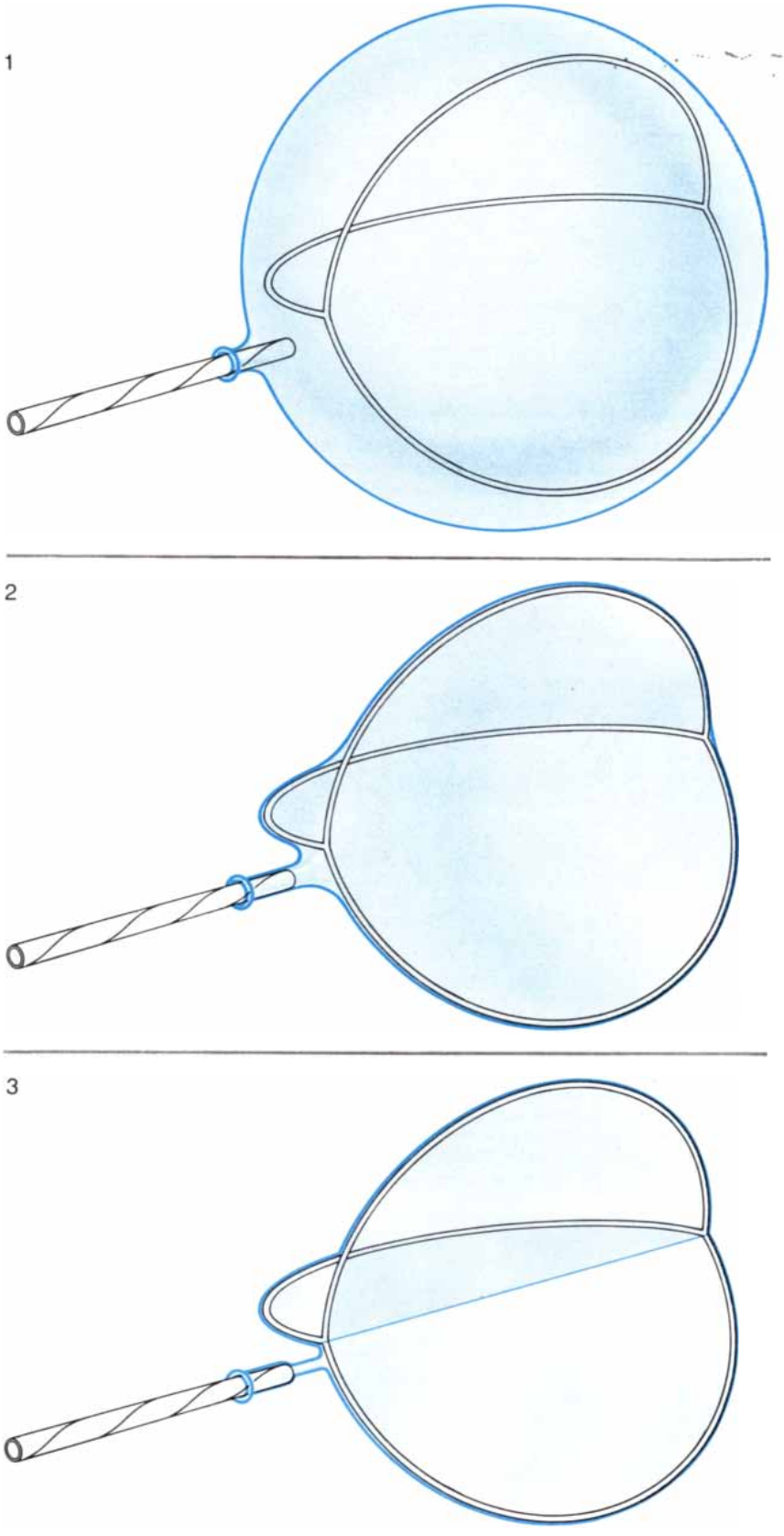

**SURFACE TENSION of a liquid arises as a result of the unbalanced attractive forces that exist between molecules at the surface of the liquid. These forces, indicated here by two-headed arrows, are particularly strong between polar molecules, such as those of water, which have an asymmetrical distribution of electric charge. In the absence of gravity and air pressure the surface of a liquid will act as an elastic membrane, tending to minimize surface energy per unit area.**




**EFFECT OF SOAP ON WATER is illustrated in this schematic diagram. In contrast to the polar molecules of water, the molecules of a soap or a detergent consist typically of a long, slender nonpolar hydrocarbon chain with a highly polar oxygen-rich group attached at one end. When such molecules are added to water, they tend to migrate to the surface and orient themselves so that their nonpolar ends are sticking out, thereby reducing the surface tension. When the layer of soap molecules is stretched, however, say by a moving wire or a puff of air, the surface tension is increased, owing to the temporary decrease in the number of soap molecules per unit area. This effect gives the surface of the liquid additional stabilizing elastic properties.**



**SECOND IMPORTANT EFFECT of soap on the formation of a liquid film is to limit the thinness of a film made from soapy solution to the length of two soap molecules stacked end to end.**




**WATER-FILLED BALLOON collapsing on a wire frame as the water is extracted by a straw through the neck is offered as a gravity-free analogy to the way a soap film is formed as a wire frame is removed from soapy water. Up to a point the tension in the skin of the balloon is sufficient to force the water out. Thereafter the water must be sucked out through the straw, in effect increasing the surface area of the balloon. In the formation of an actual soap film on a wire frame (such as the one shown in the color photograph at the top of page 83) the force of gravity acting on the water inside the film serves to achieve a similar increase in the area of the film.**

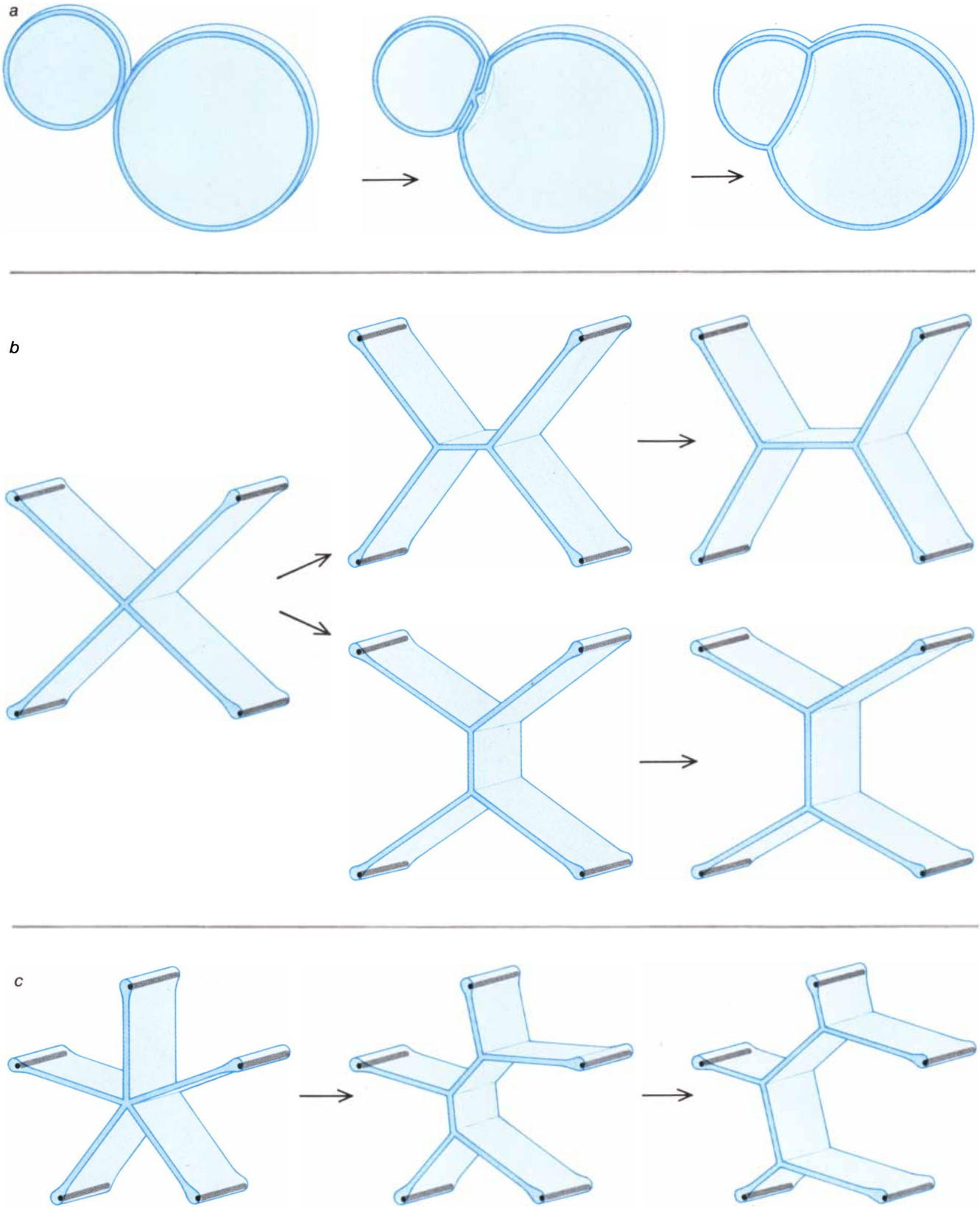
to answer such questions affirmatively, what can one say mathematically about the geometric structure of such soap-film-like and soap-bubble-like configurations of surfaces?

The hope would be, of course, that the answers to these mathematical questions are closely related to the observed existence and geometric structure of actual soap films and soap bubbles. As it turns out, the mathematical conclusions and methods of analysis do seem to mimic to a high degree how soap films and soap bubbles actually behave. In particular, mathematical configurations of surfaces that are soap-bubble-like and soap-film-like do exist for all appropriate frames. (A single straight line segment, for example, would not be considered an appropriate frame for a soap-film-like configuration.) Furthermore, any such configuration of surfaces must of mathematical necessity conform exactly to the three geometric principles stated at the beginning. To be sure, the mathematical theorem is not a physical proof that soap films and soap bubbles have to behave that way; it is merely a statement that the area-minimizing principle embodied in the definition of soap-film-like and soap-bubble-like surface configurations is in itself completely adequate to account for the overall geometry of soap films and soap bubbles. All things considered, it does not seem unreasonable to think the geometry is in fact determined that way.

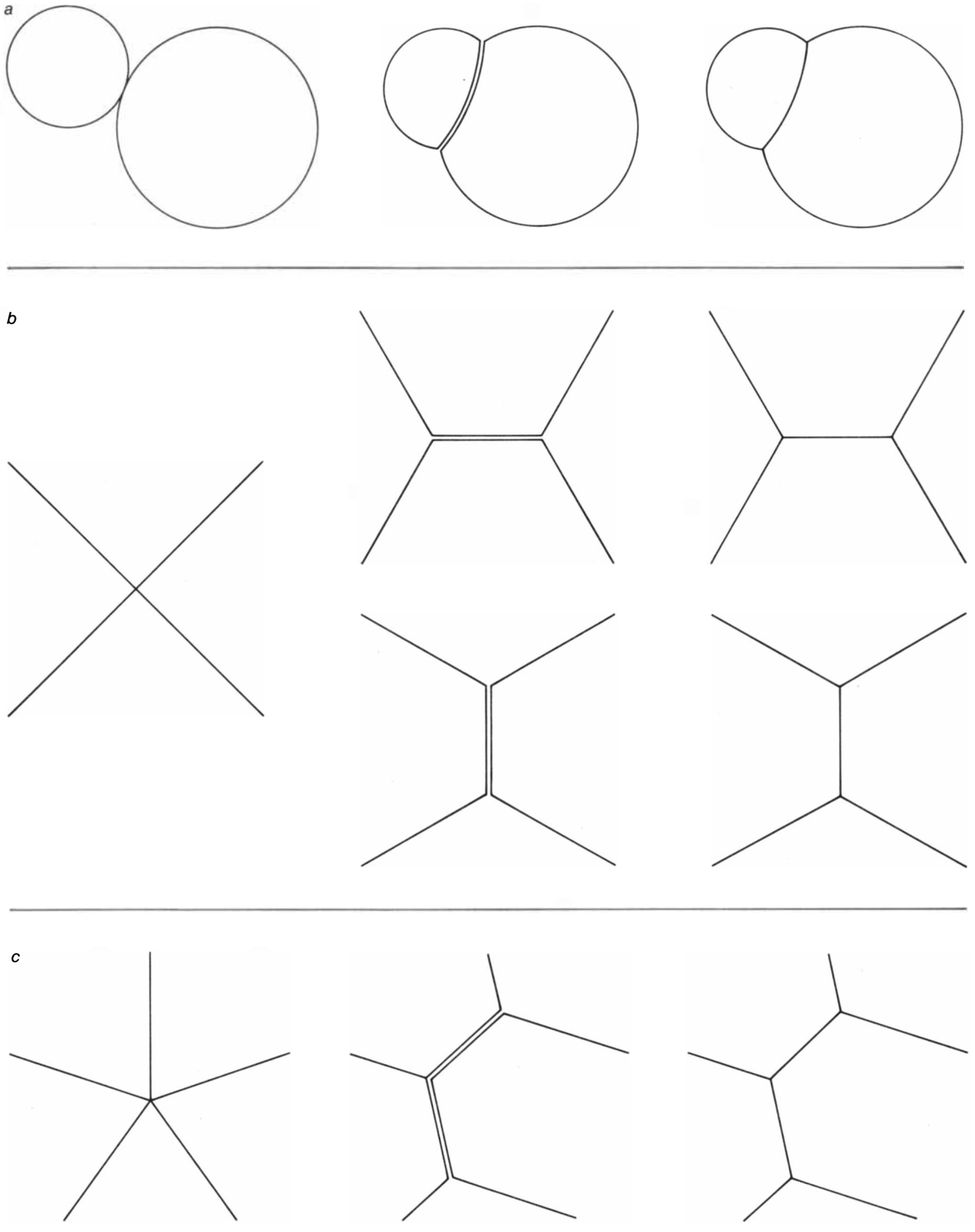
We shall be discussing in somewhat more detail the nature of the mathematics that had to be created for this type of geometric analysis. The striking simplicity of the initial hypotheses and the resulting conclusions are unfortunately in marked contrast to the complexity of the mathematics that links them.

The single most important factor that leads to this complexity is the nature of the changes in geometric configuration with which one has to deal. In particular, in the deformations considered here two separated pieces of surface are allowed to make contact with each other, stick together and thereafter be counted as a single piece of surface. Moreover, junctions where several surfaces meet are allowed to slide apart, thus introducing new pieces of surface where previously none existed. The changes of structure one must allow in order to have a realistic model of soap-film behavior correspond to drastic changes in the geometry of the configurations being considered. The combinatorial relations between the various pieces of surface and even the number of these pieces clearly can change dramatically under the changes allowed a soap film. There seems to be no reasonable way to estimate ahead of time an upper limit to the amount of this complexity, and one is therefore obliged to deal mathematically with surfaces whose structural complexity is potentially unbounded.

A word about frames is appropriate at this point. In making actual soap films the wires one uses for frames have a substantial




**SOAP FILMS CAN CHANGE** in several ways to decrease their total surface area, as the enlarged cross-sectional diagrams on this page demonstrate. In *a* two soap bubbles are brought together to form a compound bubble. At the moment the two bubbles start to join, the water inside one bubble begins to flow into the water inside the other at the point of contact. In the final configuration parts of two surfaces are eliminated, thereby substantially decreasing the total surface area of the two original bubbles. In the highly unlikely configuration shown in *b* four separate pieces of surface meet along a straight line segment. Such a configuration is bound to change promptly to decrease its total exposed area by following either the upper or the lower sequence of stages. In *c* an even more unlikely meeting of five soap films is shown, along with one of a number of sequences that it could follow to decrease its total area. In all three of the examples depicted in the illustration on this page the separate surfaces meet in the final configuration at angles of 120 degrees with respect to one another.



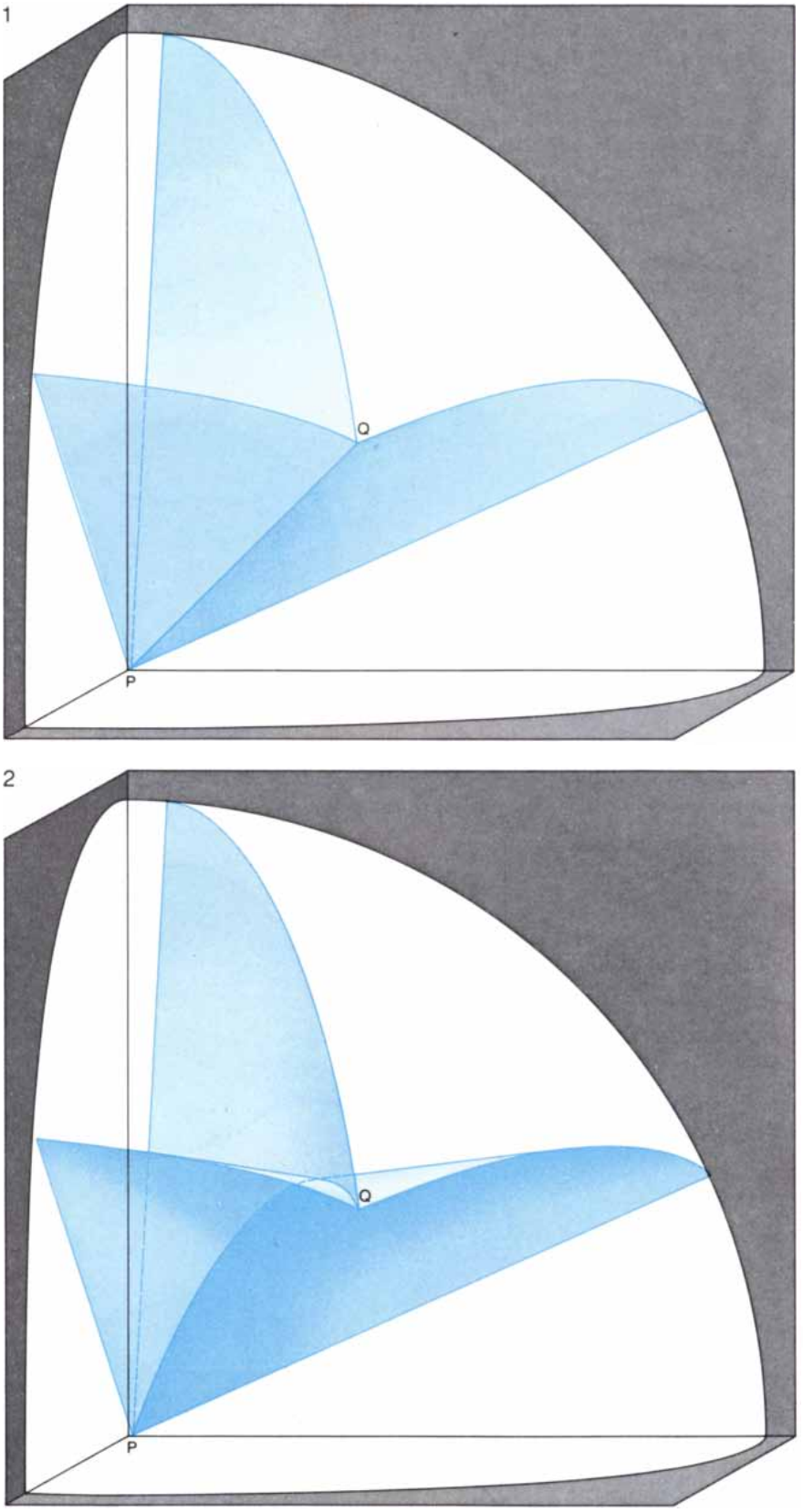

**MATHEMATICAL MODEL of the behavior of soap bubbles and soap films reproduces the essential geometric features of the physical model illustrated on the preceding page. The three-dimensional multilayered physical soap films of that illustration are represented here as pieces of two-dimensional surfaces shown in cross section. According to the mathematical model, a geometric configuration of two-dimensional surfaces is said to be soap-film-like if it cannot be made to have a smaller area by any small deformation that leaves some given wire frame fixed. If such a deformation causes two or more surfaces to coincide, the areas where the surfaces overlap are counted only once. By this definition the areas of the configurations in the middle column are therefore equivalent to those in the right-hand column.**

thickness. Often one cannot simply replace them mathematically by one-dimensional line segments or curves. Indeed, on many infinitely thin frames there will exist no mathematical soap-film-like configurations of surfaces, although soap films readily form on similar frames constructed from real wire. A simple example of such a frame is a loose overhand knot tied in a length of wire, leaving both ends free [*see top illustration on page 84*]. No mathematical soap-film-like configuration of surfaces can form within an infinitely thin curve in the shape of such an overhand knot. Another curious property of this particular soap film is that it does not "span" its wire-frame boundary in any of the mathematical senses familiar to topologists. This phenomenon of a soap film that does not span a topologically defined hole recurs in certain mathematical soap-film-like configurations of surfaces within infinitely thin one-dimensional frames, and hence it is not peculiar to thick frames. In our model the frames can be either thick or infinitely thin. In fact, our model does not require that the "frame" resemble wire at all; a frame for a soap-bubble-like configuration could also be provided by a tabletop, say [*see bottom illustration on page 84*].

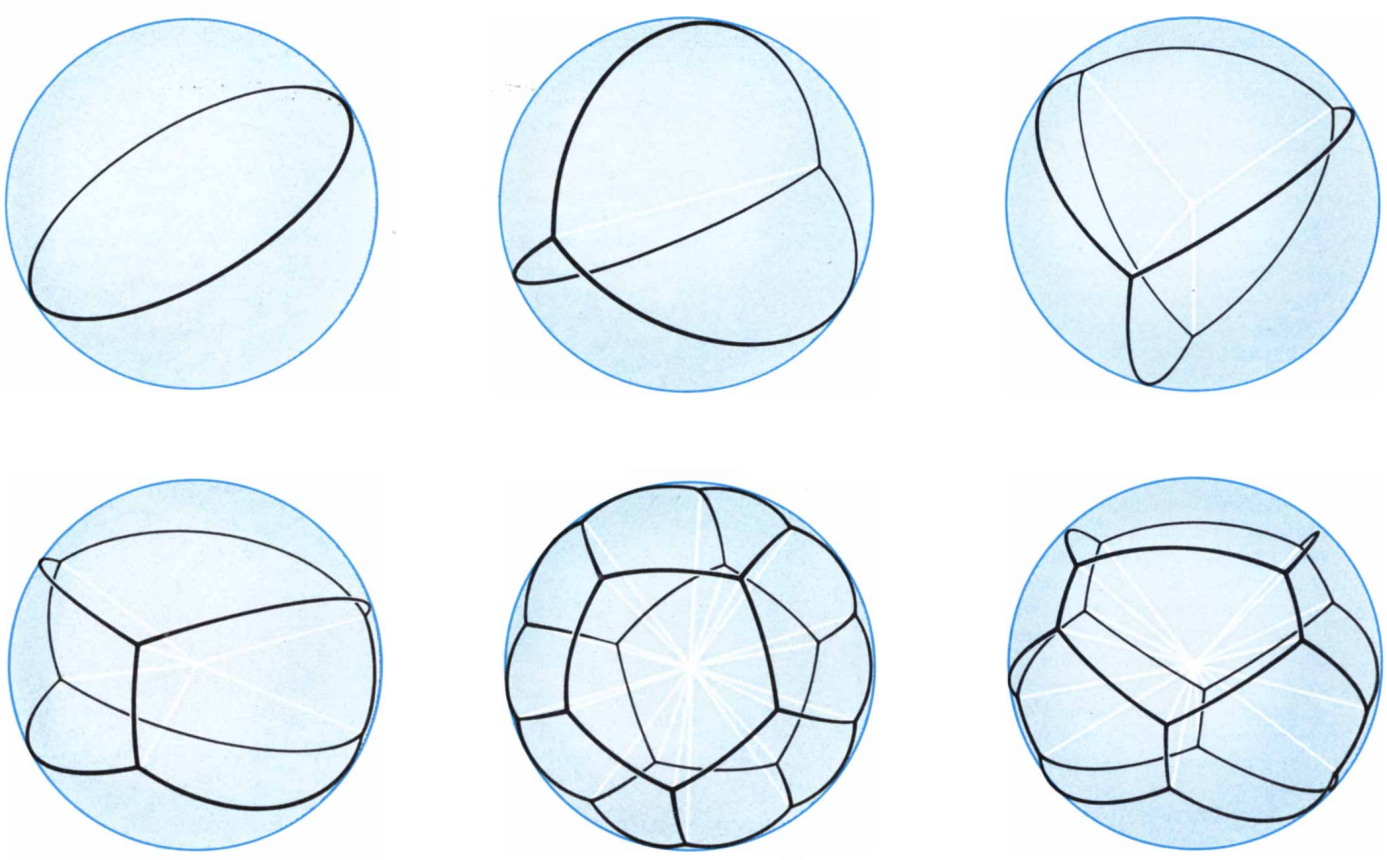
It is not difficult to prove that if the structure of a soap-film-like or soap-bubble-like configuration of surfaces were known ahead of time to be finite and to consist of flat or very smoothly curved surfaces smoothly joined together, then Plateau's second and third principles would have to hold. Since this analysis leads to the construction of some particularly intricate and beautiful soap films, we shall outline it here.

To begin the analysis one picks a point on the configuration of surfaces and figuratively examines that point under an increasingly high-power microscope. As the magnification increases, the surfaces seem to become increasingly flat. Because of this increasing flatness one can readily show that the truth or falsity of the second and third principles for soap-bubble-like and soap-film-like configurations depends only on their truth or falsity when they are applied to soap-film-like configurations made entirely of pieces of surface that are already flat and that meet one another along straight-line segments, which may in turn meet at various vertexes. Consider then such a finite flat configuration; at any branching point in the configuration there is a small sphere centered on the point so that the intersection of the configuration with the sphere consists only of flat pieces that include the point on one of their edges or corners. Thus the soap-film-like configuration will intersect the two-dimensional surface of the sphere in a configuration of pieces of one-dimensional curves that are parts of great circles lying on the sphere.

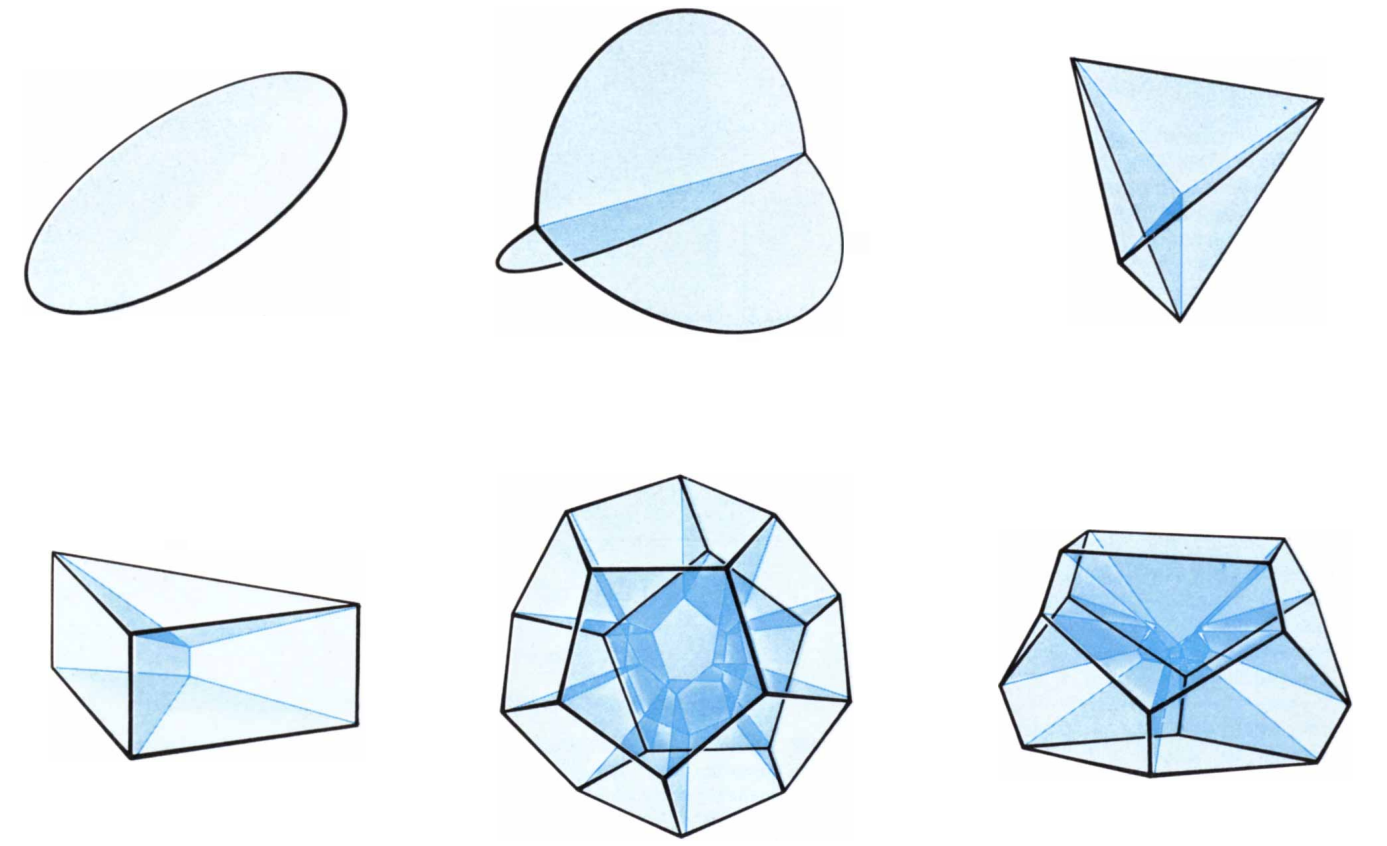
One now examines the possible configurations of such pieces of great circles that one might obtain by intersecting suitable small spheres with flat soap-film-like config-



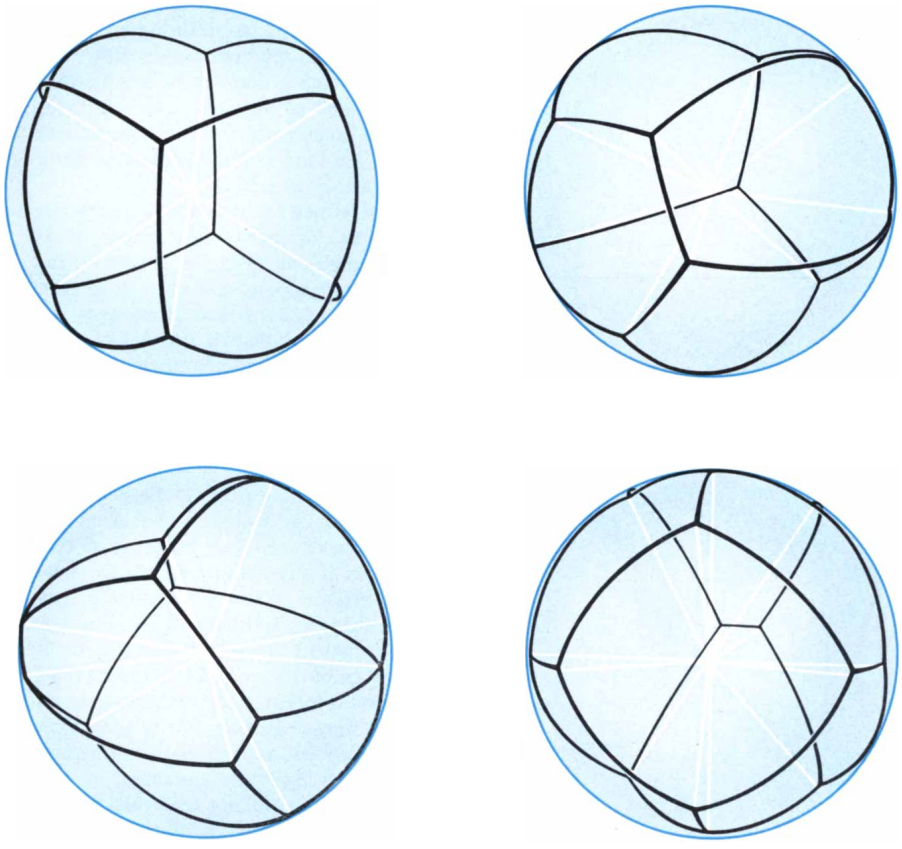

**ONE TEST for determining whether a given mathematical configuration of surfaces could be soap-film-like or not is presented in this illustration. If a configuration of flat surfaces all containing the same point (*P*) is soap-film-like, then the intersection of these planes with a sphere centered on that point must consist of segments of great circles meeting three at a time at angles of 120 degrees. If at a point (*Q*) on the surface of the sphere the angles of meeting were other than 120 degrees, as shown in the top diagram, then a deformation of the space inside the sphere, as shown in the bottom diagram, would decrease the total area of the surfaces, demonstrating that the original mathematical configuration of flat surfaces was not in fact soap-film-like.**



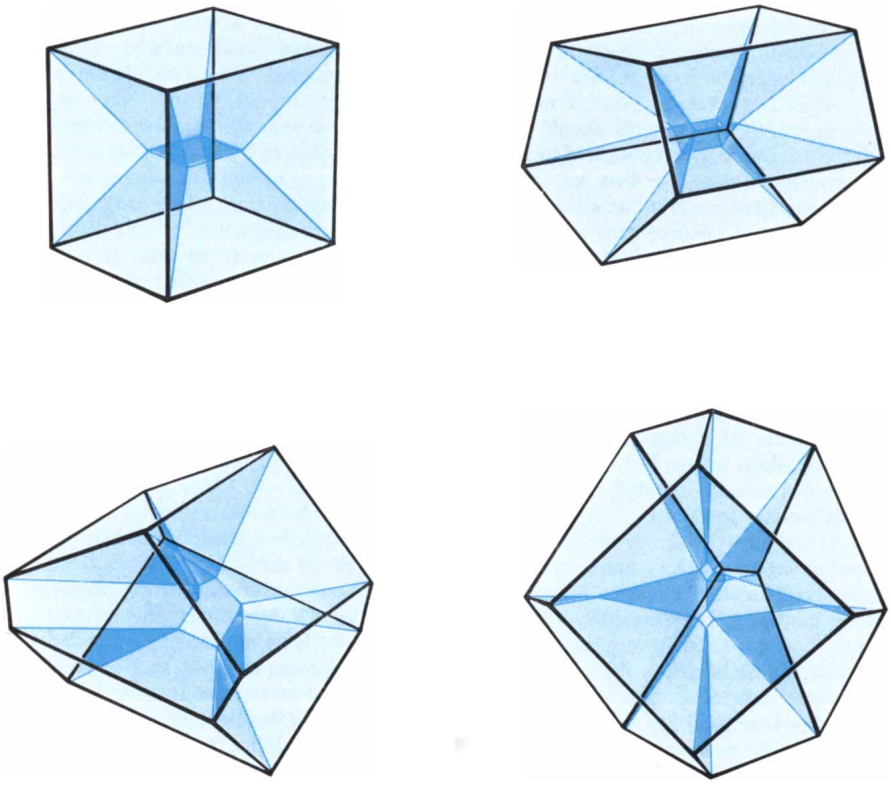
**TEN POSSIBLE CONFIGURATIONS** of great-circle arcs that meet three at a time on the surface of a sphere with angles of 120 degrees at their vertexes are drawn in this illustration. One asks for each configuration in turn whether or not there exist small deforma-



**DEFORMATIONS CAN BE FOUND** corresponding to every case cited above except the first three, thus proving that the seven remaining original configurations of flat surfaces (and their curved versions) are in fact not soap-film-like or soap-bubble-like. Most of the math-



**tions capable of decreasing the area of the configuration of flat surfaces that would have given rise to that particular configuration of circular curves. The answers are given in illustration below.**



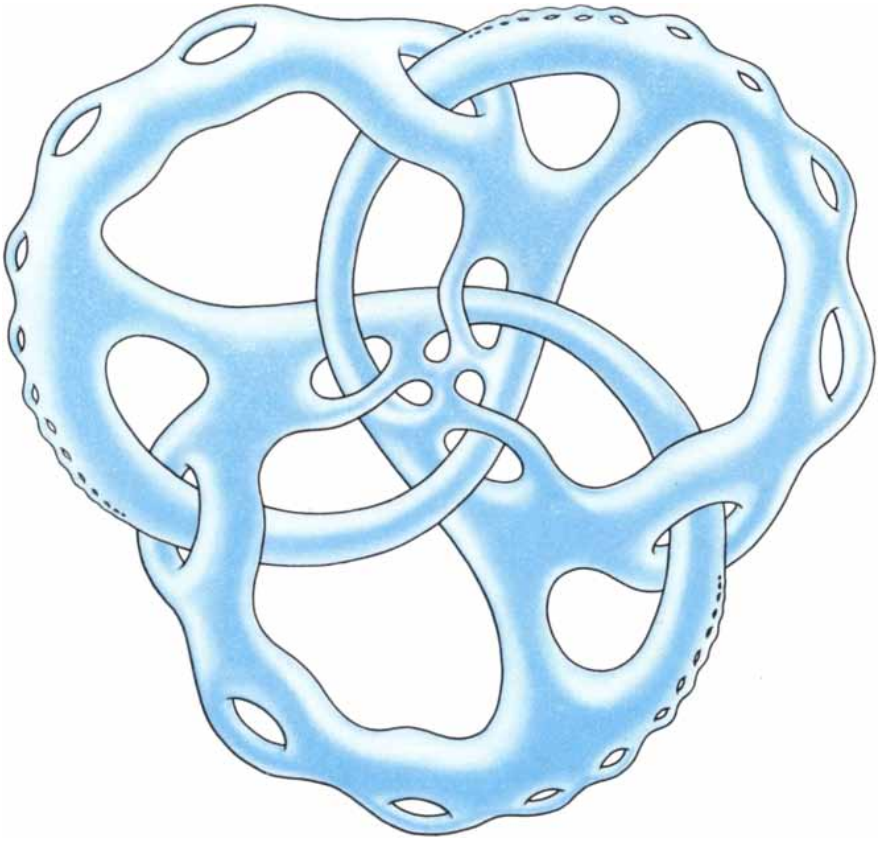
**ematical deformations represented here for those seven configurations were discovered by the authors by studying the shapes of actual soap films that formed on the appropriate wire frames.**

urations. First one notes that at each vertex where several great-circle segments meet, the number of segments meeting there must be exactly three and they must meet at equal angles of 120 degrees with respect to one another. Indeed, if that rule did not hold at a vertex, then one could readily decrease the area of the configuration within the sphere by a small deformation [*see illustration on page 89*].

It turns out that one can determine by means of spherical trigonometry alone all the possible configurations of pieces of great circles on spheres that meet three at a time with equal angles at their vertexes. There are exactly 10 such configurations [*see top illustration on these two pages*]. For each of them in turn one asks whether or not there are small deformations capable of decreasing the area of the configuration of flat pieces that would have given rise to this particular configuration of curves; in constructing such deformations one is not allowed to move the surface along the sphere itself, because if one did, the configuration inside the sphere would no longer be connected to the original configuration outside the sphere. As it happens, one can find such deformations in every case except the first three [*see bottom illustration on these two pages*]. The mathematical deformations found were in fact discovered in several cases by making wire frames and studying the shapes of the actual soap films that formed. Since the deformations show that the original configurations of flat pieces are in fact not soap-film-like (by definition a configuration is soap-film-like only if no small deformation decreases its area), these configurations and their curved versions cannot exist in any soap-film-like or soap-bubble-like configuration of surfaces.

How does this analysis now yield Plateau's second and third principles? The configuration that would have given rise to a single great circle is a single plane, so that the point in question would not have been a branching one. The configuration that would have given rise to three half great circles meeting at 120 degrees at the antipodal points consists of three planes meeting along their edges along a diameter of the sphere at equal angles of 120 degrees. The configuration that would have given rise to six equal segments of great circles meeting three at a time with equal angles at the vertexes of a regular tetrahedron consists of six wedge-shaped planes meeting three at a time along four straight lines that in turn meet at the center of the sphere at equal angles. Thus the only possible ways flat pieces of surface can meet in a soap-film-like configuration are precisely those allowed by the empirical principles we have cited. It is therefore possible to conclude that these principles apply to any soap-film-like or soap-bubble-like configuration of surfaces one knows ahead of time to be smooth and finite.

Do there actually exist mathematical soap-film-like and soap-bubble-like configu-



**HYPOTHETICAL SURFACE of finite area but unbounded complexity can be represented mathematically as a measure, that is, a function that assigns a certain value to an arbitrary subset of space and satisfies a few additional conditions. The new approach to geometry known as geometric measure theory enables mathematicians to treat immensely complicated configurations of surfaces, such as soap-film-like and soap-bubble-like configurations, with precision.**

rations of surfaces corresponding to various frames and prescribed volumes? If so, do such configurations of mathematical necessity consist of smooth pieces of surface meeting smoothly along smooth curves that in turn meet smoothly at isolated points?

Motivated by, among many other things, the desire to provide realistic mathematical models for geometric configurations such as those of soap bubbles and soap films, mathematicians have created new types of mathematical surfaces and have begun to study them intensively. These new surfaces are actually two mathematical steps away from common experience, and a brief introduction to them is in order.

The study of such geometric properties as the length of curves, the area of surfaces and the volume of solids dates back to the ancient Greek mathematicians and perhaps even to earlier times. As long as the particular geometric figures one is considering are fairly elementary there is no serious doubt about what their length, area or volume should be. The expanding horizons of mathematics over the past century or so have led to thorny questions about what length or area or volume "should" be assigned to certain complicated sets. Attempts to resolve questions such as these led to the creation of a mathematical theory of measurement called measure theory.

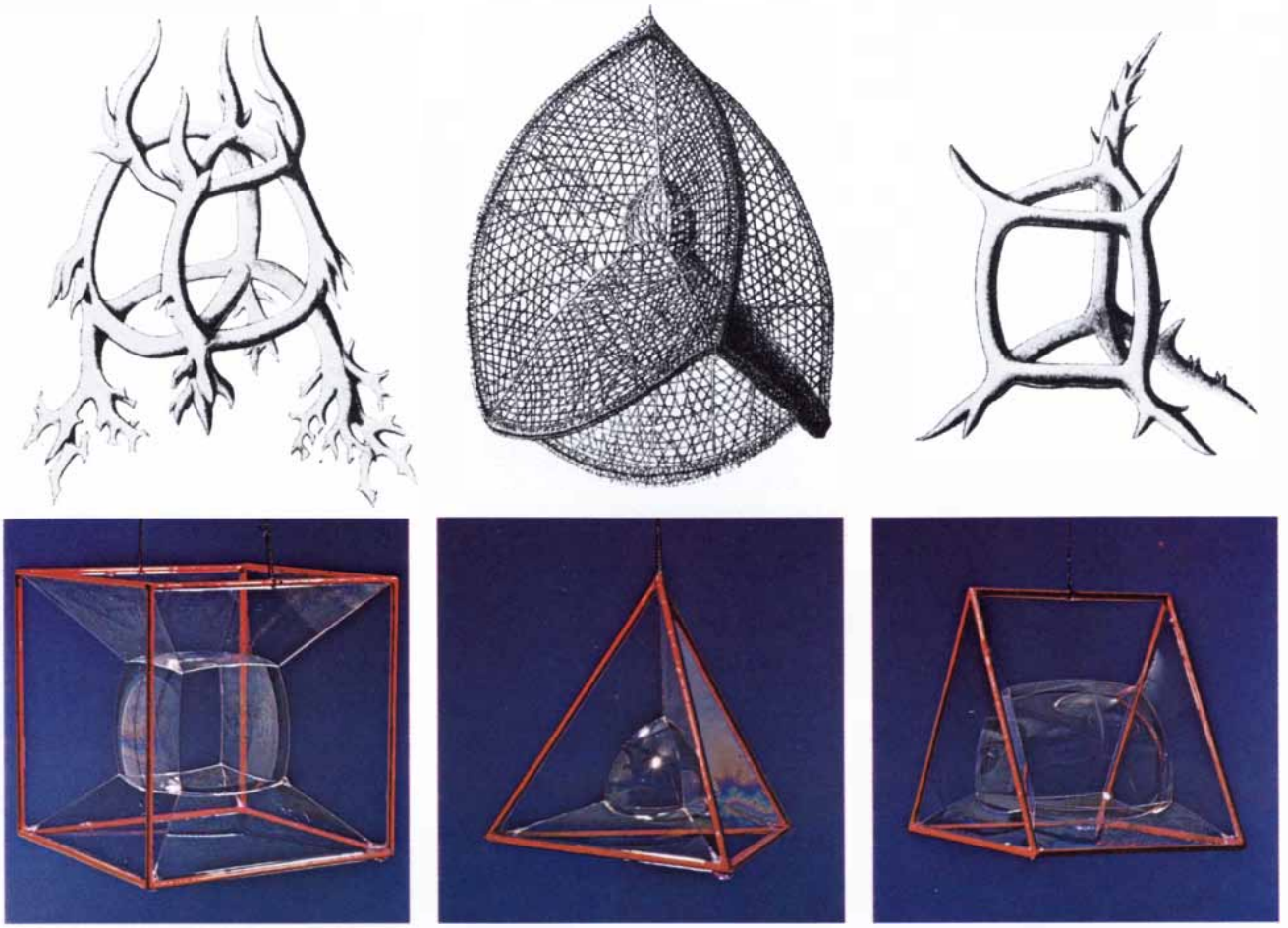
One of the basic definitions in measure theory is that of a measure itself. A one-dimensional measure is a function that assigns to each subset of space a number called its length; that number should agree with the usually accepted notion of length if it is naturally defined for that set. (Sometimes the number is infinite, as would be the case for a set of positive area or a set of positive volume.) Similarly, a two-dimensional measure is a function that assigns to each set a number called its area, and a three-dimensional measure is a function that assigns to each set a number called its volume. The general measures studied in this theory do not necessarily correspond to any dimension but rather are simply functions that assign to sets in space a positive number (or zero or infinity) and satisfy a few additional conditions.

A central idea in the newer subject of geometric measure theory has been to turn things around a bit, in a fashion not uncommon in mathematics. Where originally one regarded, say, a two-dimensional measure as a tool for determining the area of any surface one might encounter, it turns out to be of considerable utility to turn surfaces themselves into measures that are then capable of measuring their own areas! Stated somewhat more precisely, a surface that has become a measure assigns to an arbitrary subset of space the amount of the usual area of the surface that is inside that subset. One of the many advantages of this approach to geometry is that mathematicians now have a way of treating immensely complicated configurations of surfaces—even surfaces of infinite complexity—with mathematical precision, as long as the total area is finite [*see illustration at left*].

In this framework it is not very difficult to prove the existence of measures as "solutions" to problems. The rub is that at this point these solutions are only measures. Fortunately mathematical techniques for uncovering the geometric content of measures such as these can be utilized, and one is able to prove with complete rigor that a solution measure comes from pieces of two-dimensional surfaces that are smooth on their interiors and that the configuration of these surfaces is a legitimate mathematical candidate for a soap-film-like or soap-bubble-like surface. It is paradoxical that knowledge of the manner in which these various surfaces would fit together if they did so smoothly enables one (after considerably more work) to conclude that they do fit together smoothly in that manner. This conclusion is the final step in the mathematical modeling of the behavior of soap films and soap bubbles, since the basic mathematical questions have been answered.

It is worth remarking that this type of mathematical modeling is quite flexible. It can be adapted to handle a number of variants of the problems we have mentioned, and the nature of the conclusions does not depend in an excessively delicate way on the precise nature of the hypothesis. Possible variants of the problem include in particular the modeling of the idea of a balloon shrinking down on a wire frame, using three-dimensional "thick surfaces" instead of two-dimensional surfaces and taking into account gravitational effects. The techniques can also be applied to other problems involving surface energy, such as determining the shape of a liquid in a container of any form when capillary effects are present. The study of geometric configurations changing with time is an area of active mathematical research with many potential applications.

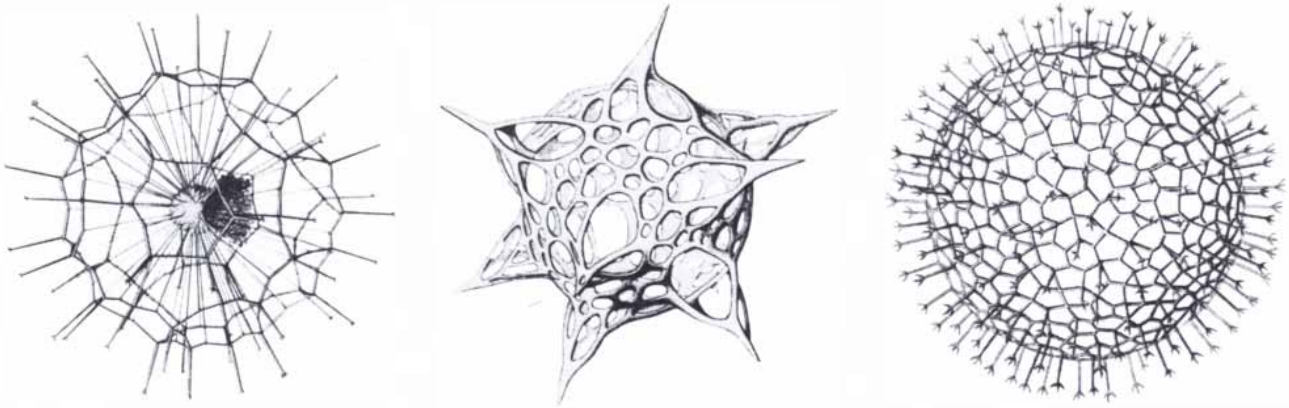
In his celebrated book *On Growth and Form* D'Arcy Wentworth Thompson cites numerous examples suggesting that the shapes of many living things are largely determined by the application of elementary mathematical principles. Of special interest here is Thompson's study of the manner in which surface tension can determine such shapes. In particular he discusses the tiny marine organisms called radiolarians, some of which beautifully illustrate the principles we have outlined in this article. When radiolarians are alive, they consist of a small mass of protoplasm surrounded by a soap-bubble-like froth of cells. As with soap bubbles and soap films, the fluid in the interfaces of the froth accumulates primarily at the branchings, and the animal acquires an exquisite glassy skeleton by the deposition of a solid out of the fluid. When the animal



**SOME EXAMPLES DRAWN FROM NATURE provide a striking visualization of the mathematical principles outlined in this article. The drawings at the top, reproduced from Ernst Haeckel's *Report on the Scientific Results of the Voyage of the HMS Challenger during the Years 1873–1876,* portray the microscopic skeletons left after the death and decay of several types of radiolarian, a tiny marine organism that in life consists of a small mass of protoplasm surrounded by a soap-bubble-like froth of cells. As the color photographs under the drawings show, the branchings of the radiolarian skeletons, where the silica-bearing fluid in the interfaces of the froth tends to accumulate, bear a strong resemblance to the branchings of soap bubbles blown into centers of soap-film configurations formed on wire frames.**

dies, everything decays except the skeleton. These skeletons provide a striking visualization of the branchings of the froth: the pieces of curves and the vertex points. Some of them also show the shapes of the cell walls.

In summary, we have undertaken to demonstrate how a few observations concerning the way in which soap films and soap bubbles are free to change to decrease their energy form the basis of a mathematical model of soap-film-like and soap-bubble-like configurations of surfaces. By mathematical analysis alone one can then show the existence of such soap-film-like and soap-bubble-like configurations corresponding to various frames and enclosed volumes and prove that they must precisely obey the three principles, first formulated by Plateau, that govern the observed geometry of real soap films and soap bubbles. Indeed, the area-minimizing principle alone is sufficient to account for the overall geometry of soap films and soap bubbles.



**MORE EXOTIC EXAMPLES of radiolarian skeletons also appear in the Haeckel book. The manner in which the surface tension of the liquid in a soap-bubble-like froth can determine such shapes was first pointed out by the British naturalist D'Arcy Wentworth Thompson.**

# Appendicularians

*These small marine animals build themselves a gossamer house out of mucus. The house incorporates an elaborate apparatus for filtering food particles out of the seawater*

by Alice Alldredge

The waters of the open ocean are, among other things, a world of beautiful and delicate organisms that are adapted to an existence of floating or feeble swimming. They are the plankton, both plant and animal. They have evolved clever mechanisms for meeting the problems of life in a totally fluid and surfaceless environment. Many of the single-celled phytoplankton (the plant plankton) are equipped with long spines or globules of oil that keep them from sinking. Some of the zooplankton (the animal plankton) float with the aid of tiny gas bubbles. The zooplankton are particularly well adapted for avoiding capture by predators that search for food visually: many of them are as transparent as the watery medium in which they live.

Since the phytoplankton are minute in size and often scarce, the herbivorous zooplankton have developed a marvelous array of methods for capturing them. Many of the copepods, ubiquitous marine crustaceans, filter the single-celled phytoplankton out of the water by passing the water through tiny bristles on their appendages. The pteropods, wing-footed marine snails, collect phytoplankton on floating webs of sticky mucus. The most remarkable and most specialized of all the feeding adaptations of the zooplankton belong to the tiny tadpolelike members of the class Appendicularia. The appendicularians build and live inside a small balloon of mucus that is equipped with miniature filters that concentrate their food. Their small house is remarkably efficient at capturing particles; it can even trap bacteria in large numbers. It also protects the animal and helps to keep it afloat.

Most appendicularians filter out and ingest phytoplankton cells that have a diameter of less than five micrometers (five thousandths of a millimeter). The phytoplankton they consume belong to many groups, including the coccolithophorids, the naked flagellates, the small diatoms and the dinoflagellates. These small organisms are known collectively as the nanoplankton (from the Latin *nanus,* dwarf). Although the nanoplankton are abundant, few of the zooplankton, including the ever present copepods, are able to capture them. The appendicularians manage the task easily and efficiently with their bubble of mucus. Indeed, many of the nanoplankton were first described by the 19th-century German biologist Hans Lohmann after he had found them in the filters of appendicularians' houses.

Appendicularians belong to the phylum Chordata, which includes the vertebrates. They form a class in the subphylum Urochordata, or Tunicata. Appendicularians and other tunicates are primitive compared with the vertebrates (members of the subphylum Vertebrata), but they exhibit three features that are common to all chordates at some stage in their life: gill slits, a tubular nerve cord and a rodlike notochord, or primitive spinal column. Some tunicates, such as the ascidians (sea squirts) are planktonic only during their larval stage; they dwell on the bottom after they reach adulthood. The appendicularians are free-swimming and lead a planktonic existence for their entire life.

Although appendicularians have not attracted much attention from biologists, they are among the commonest members of the zooplankton community: in many bodies of water they are the second or third most abundant group. There are three families of appendicularians, which are further subdivided into 13 genera and some 70 species. The species are thus comparatively few, but many are cosmopolitan; they can be found in all the oceans of the world, including the Arctic Ocean. In fact, species that are primarily warm-water forms are sometimes collected in polar waters.

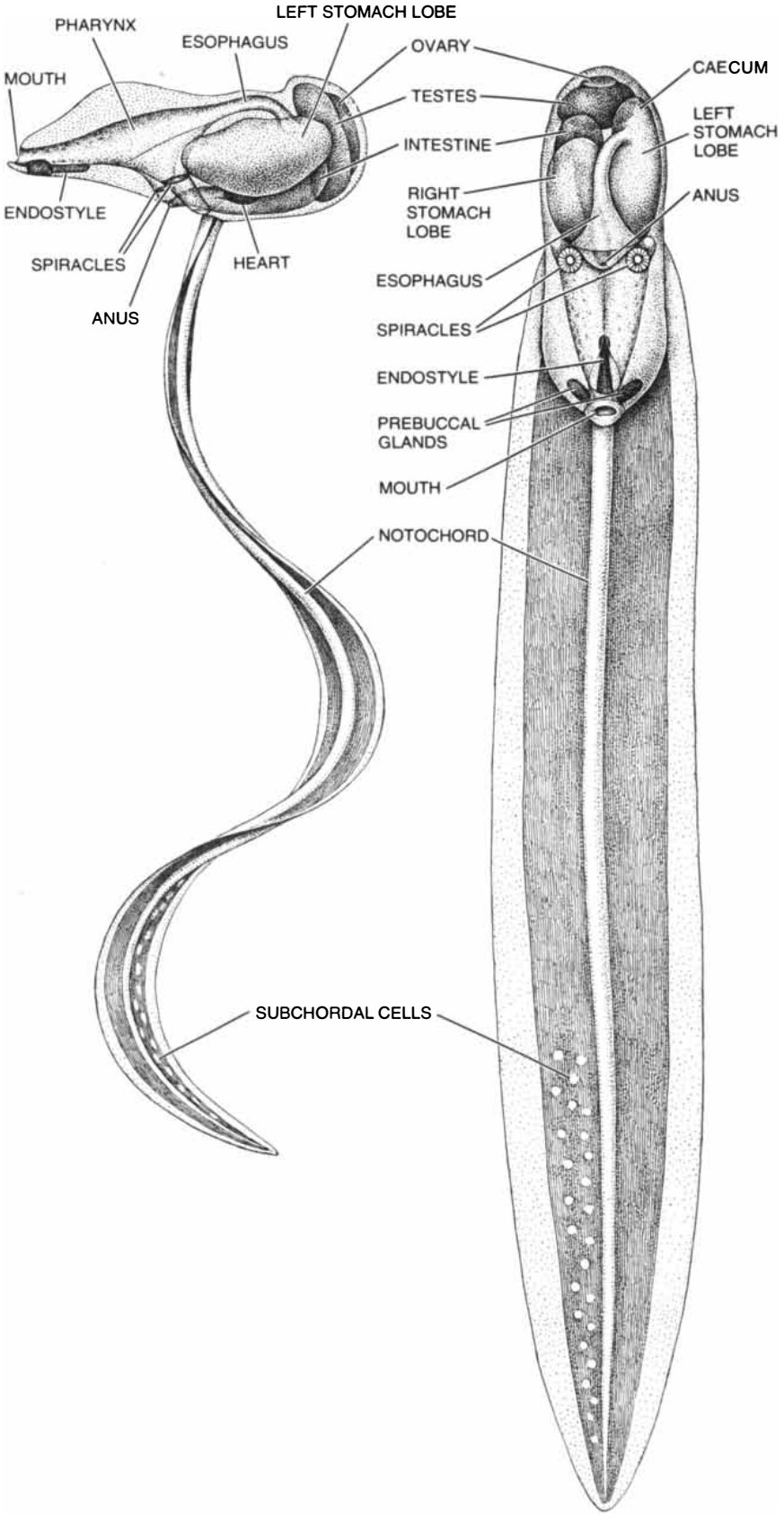
Numerous though they are in the open ocean, appendicularians are most abundant in coastal waters and over the continental shelves. It is there that the phytoplankton are most readily available. Moreover, appendicularians are generally found in the top 100 meters of the water. That illuminated surface layer, the euphotic zone, is where the photosynthetic activity and the density of the phytoplankton are greatest. Many of the zooplankton migrate through a considerable vertical distance with the daily cycle of daylight and darkness, but this is apparently less true of the appendicularians; they tend to remain in the surface waters.

Most appendicularians are shaped like a bent tadpole. The animal has two parts: an egg-shaped trunk and a flexible and muscular tail. The tail is thin and flat, resembling the blade of a knife; it is attached to the lower surface of the trunk between half and two-thirds of the way back from the front end of the animal. It consists primarily of muscles and a stiff notochord that runs longitudinally down its center.

The trunk contains all the major organs, including the reproductive and digestive systems. The mouth, at the front end of the trunk, is connected externally to the mucus house and internally to a large pharynx. The pharynx leads into a *U*-shaped digestive tract that consists of a stomach, an intestine and an anus, which empties near the base of the tail. An elongated gland, the endostyle, is located near the mouth and manufactures mucus as the animal feeds. The gill slits are connected to the pharynx by spiracles lined with cilia, which draw water laden with food particles through the mouth and into the pharynx. The animal's thin blood circulates through a simple system of sinuses, pumped by a single muscular heart and the movement of the tail.

All appendicularians, with the exception

**APPENDICULARIAN'S HOUSE is the filmy pink structure in the photograph on the opposite page, made by James King of the Australian Institute of Marine Science. It is about the size of a walnut. The head, or trunk, of the animal itself can be seen as the white egg-shaped object at the center of the house; curving downward from the trunk is the animal's translucent tail. This appendicularian is a member of the species *Stegosoma magnum*. The internal structure of the house, which is normally transparent, has been made visible by red carmine dye. Water is drawn into the house through two filters to the left and right of the animal's trunk. Particles too large for the appendicularian to ingest are thus excluded. Smaller particles pass into the house and are trapped on a highly complex feeding filter in the interior of the house. The animal draws the food from the feeding filter through the strawlike buccal tube leading to its mouth.**




**ANATOMY OF AN APPENDICULARIAN consists chiefly of a digestive system and gonads. The animal shown is the typical species *Oikopleura albicans*. The two views are slightly different to display the animal's organs. The lateral view (*left*) shows the trunk pointing forward and the tail curved; the dorsal view (*right*) shows the trunk pointing downward and the tail flat. As do all members of the phylum Chordata (including vertebrates at some phase), appendicularians have a notochord (or primitive spinal cord), a dorsal nerve cord (*not shown*) and spiracles (modified gill slits). Most appendicularians have both testes and ovaries in a single animal.**

of the species *Oikopleura dioica,* are hermaphroditic: each individual has the reproductive organs of both sexes. Some species are even protanderous, that is, they have the remarkable ability to produce both eggs and sperm from the same gonad at different times. From the human point of view appendicularian reproduction is heroic. Sperm are liberated through tiny ducts to the exterior of the trunk. Eggs, however, are released only when the ovary and the rear of the trunk split open, resulting in the death of the animal. The eggs are fertilized externally in the water, probably when sexually mature appendicularians spawn together at the same time. The embryo develops very rapidly. Within 24 to 48 hours after fertilization a miniature appendicularian has developed, complete with the ability to build itself a mucus house.

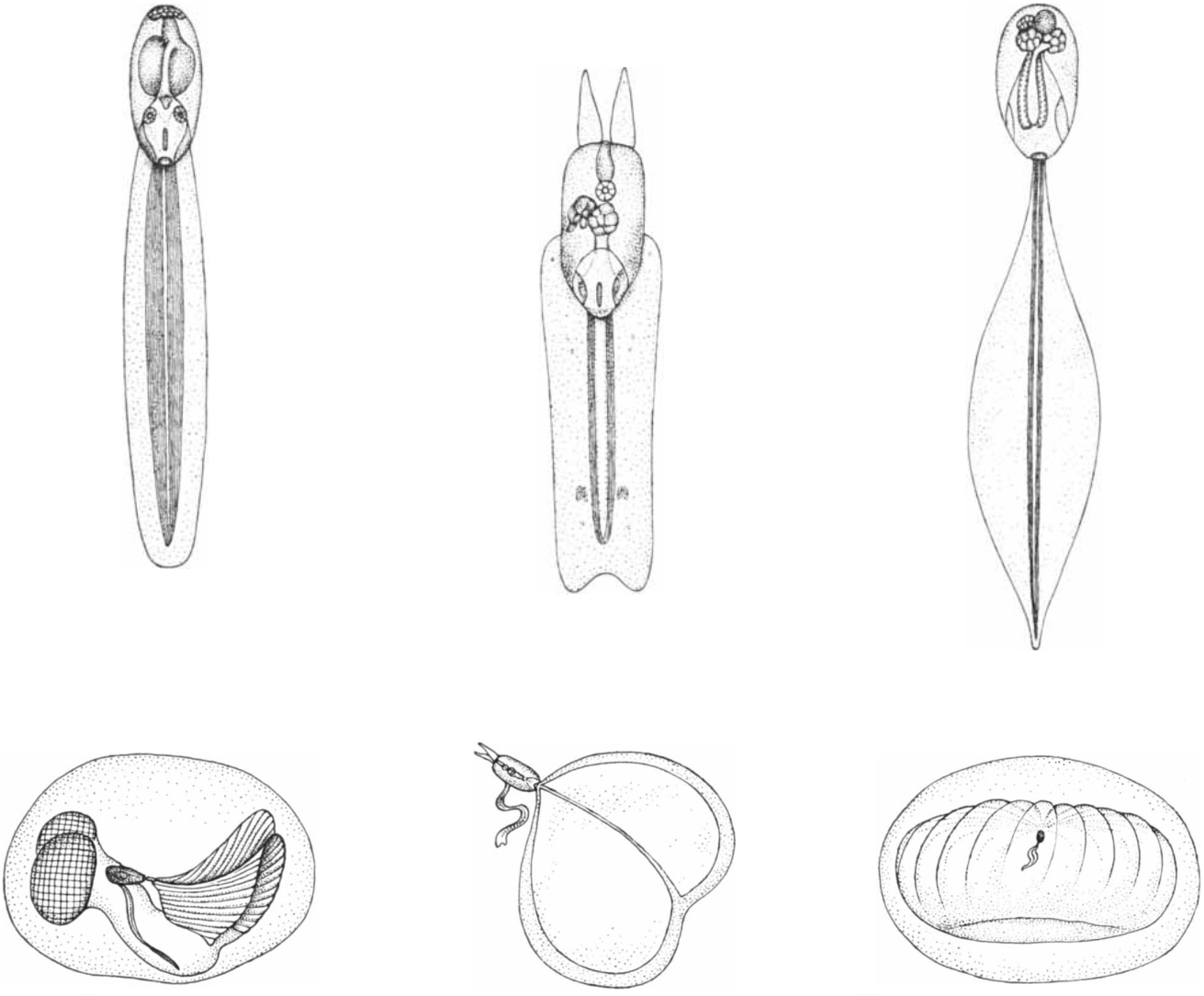
Appendicularians are generally transparent. Only the movement of their beating tail makes them visible in the water. A few species do have color; they are shades of bright yellow, red or blue-violet. The animal proper is quite small: its trunk may be only a few millimeters long. Its mucus house, however, may be as large as a walnut. And although the house is so transparent that it is virtually invisible in itself, it can usually be identified in the water because its surface and filters have trapped phytoplankton and other particles.

The three families of the Appendicularia are quite distinct in their anatomical structure. The family Oikopleurida is by far the most studied and the best-known. In the Oikopleuridae the trunk is short and compact and the tail is long and narrow. The spiracles and gill slits are located near the anus; the stomach wall is made up of many small cells. The mucus house encloses the entire animal and is structurally more complex than the houses of the other families.

In the family Fritillarida the trunk is slenderer and flatter and the tail is shorter and broader. The spiracles are at the front end of the pharynx; the stomach consists of a few large cells. In most of the Fritillaridae the house is limited to a small gelatinous bubble that is deployed in front of the mouth.

The third family, the Kowalevskiidae, is the smallest, containing only one known genus. The members of the family lack an endostyle, a heart and spiracles. The trunk is quite short and the tail is long and leaflike. The house resembles a small umbrella. Although it completely surrounds the animal, it lacks the complex filtering apparatus found in the houses of the Oikopleuridae.

On the time scale of animal evolution the appendicularians are extremely old. Members of the species *Oesia disjuncta,* a fossil appendicularian resembling the modern Oikopleuridae, have been found dating back to the Cambrian period, more than 450 million years ago. Very few fossils of any animal group predate the Cambrian. The evolution of species before that time cannot be substantiated by evidence in the fossil record. Hence most speculations on



**THE THREE APPENDICULARIAN FAMILIES are compared to show the differences between the anatomy of the animals and the structure of their houses. The house of the Oikopleuridae (*left*) and of the Kowalevskiidae (*right*) completely surround the animal like a balloon, whereas the Fritillaridae (*middle*) carry their house like a large bubble deployed in front of their mouth. Although the Oikopleuridae have been studied, almost nothing is known of the biology of the other families. Houses of all families are shown on pages 94, 100 and 102.**

the evolutionary development of the appendicularians and the other tunicates is based on the morphology and embryology of the modern forms.

The evolution of the entire phylum Chordata has been the subject of considerable controversy. The view currently held by most vertebrate and invertebrate evolutionists is that both the vertebrates and the tunicates, including the appendicularians, arose from a sedentary filter-feeding ancestor that was attached by a stalk to the seafloor. This simple pretunicate later evolved into the sedentary tunicates of today: the ascidians. The ascidians spend their entire adult life attached to one spot on the bottom, as their pretunicate ancestors presumably did. They have a short larval stage, however, in which the animal differs markedly from the adult in appearance and behavior. The larva resembles a tadpole and is planktonic; it swims actively for a few hours or days and then settles on the bottom. Its tail, notochord and nervous system are assimilated into its other tissues, and the animal metamorphoses into the sedentary adult.

It is hypothesized that at some time in the evolutionary past the larva developed gonads and could become sexually mature before entering the adult stage. At that point it no longer metamorphosed into the sedentary adult but began a new mode of life as a completely planktonic organism. In this way a larval pretunicate may have given rise to both appendicularians and primitive vertebrates.

Some evolutionists believe the ancestor of the tunicates and the vertebrates was never sedentary but was a free-swimming animal with a tail. That free-swimming protochordate developed along two lines, one leading to the vertebrates and the other to the appendicularians and to the class Thaliacea, which embraces the barrel-like planktonic tunicates including the salps and the doliolids. In this view the sedentary ascidians developed much later from an ancestral thaliacean that settled on the seafloor.

Although these two views have given rise to much speculation and many variations, it is widely accepted that the tunicates departed from the chordate line of evolution early. Although the appendicularians may share a common ancestor with the vertebrates, it is doubtful that primitive vertebrates developed from early appendicularians, regardless of similarities between them.

The appendicularians' method of feeding is unique in the animal world. The plankton-capturing mucus house they secrete, with its intricate filters and miniature nets, is one of the most complex external structures built by any organism other than man. The houses of Oikopleuridae are the only ones that have yet been described in detail. A house in the genus *Oikopleura,* one of the more common genera of appendicularians, is a hollow sphere of mucus interlaced with a variety of passages and filters. The animal occupies the center of the sphere with its mouth facing toward the

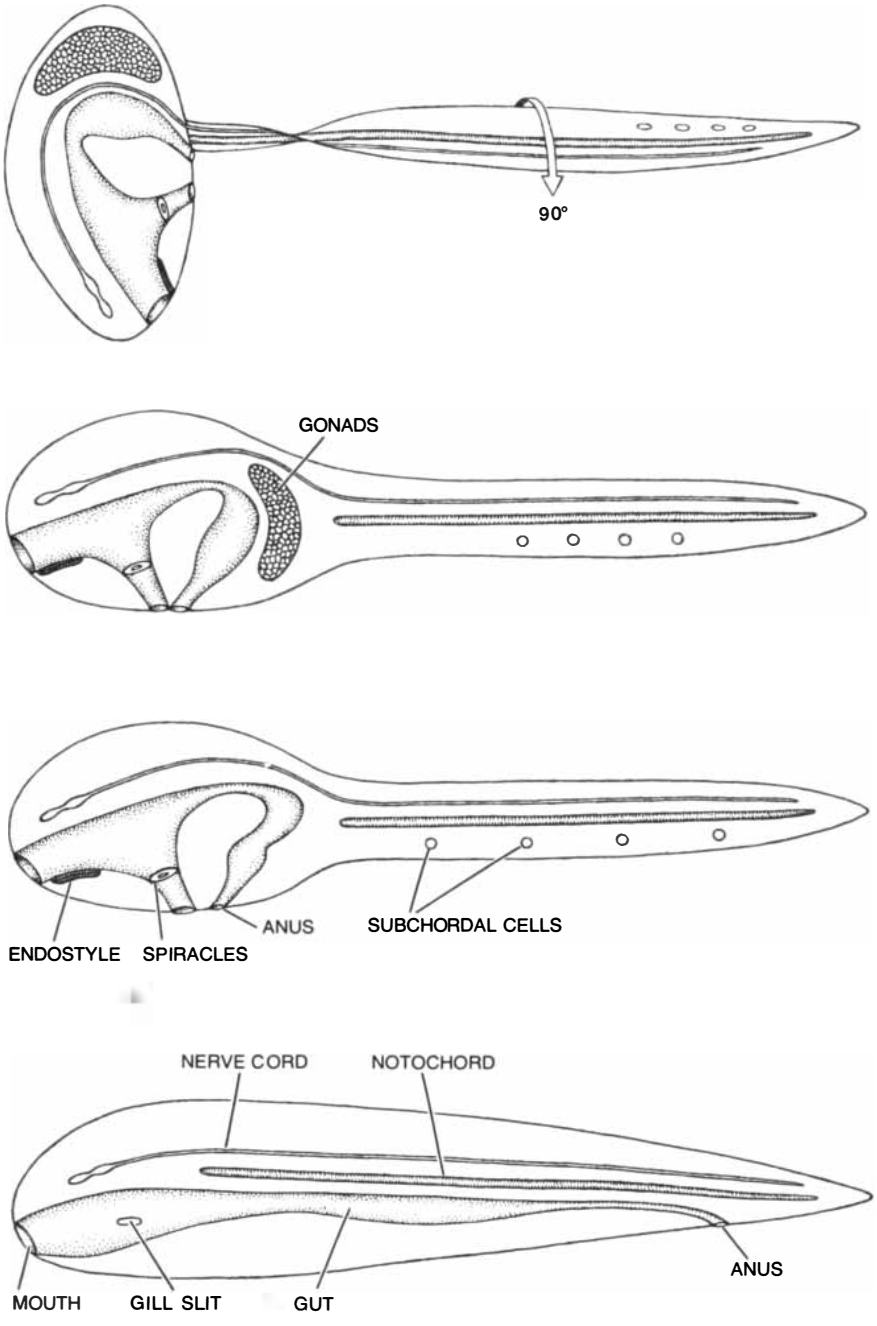
rear, as if it were sitting backward in an automobile. The outer membrane of the house is fragile and transparent. At the front end of the house are two passages through which the water enters; these incurrent passages are covered with fibers that crisscross at right angles to form a screen. Some phytoplankton cells, particularly large diatoms and dinoflagellates, are too large to pass through the filters and never enter the house. Hence the incurrent filters serve as a sorting mechanism, excluding particles that are too large for the appendicularian to ingest. The mesh size of the filters is a characteristic of each species. For example, in *Oikopleura fusiformis,* a particularly small species, the openings in the mesh average 13 micrometers across, whereas in *Megalocercus huxleyi,* a particularly large species, they may be as much as 54 micrometers across.

Two cylindrical passages lead from the incurrent filters into the house and join near the base of the animal's tail, forming a single passage. The animal's tail actually occupies this passage, and its sinusoidal beating draws water into the house through the filters. The passage diverges again at the tip of the tail and joins each side of an internal feeding filter, where tiny food particles are concentrated. This feeding filter is a complex three-dimensional structure in the form of two backward-curved wings connected along one edge. The wings are a sandwich of at least two and possibly three convoluted membrane sheets, between which the water flows. The wings of the feeding filter join at a median channel. At one end the channel is connected to the appendicularian's mouth by a hollow straw-like tube; at the other end it opens into an exit passage leading back to the exterior.

Water, pumped by the appendicularian's muscular tail, enters the house through the incurrent filters, where the large particles are removed; it travels down through the tail chamber and out to the base of each wing of the feeding filter. It then flows simultaneously up both edges of the arched wing to its apex and down between the membranes to the median channel. When the water reaches the median channel, it flows out of the house through the exit passage. Sometimes the force of the outflowing water propels the house forward. All the water must go through the feeding filter before passing out of the house.

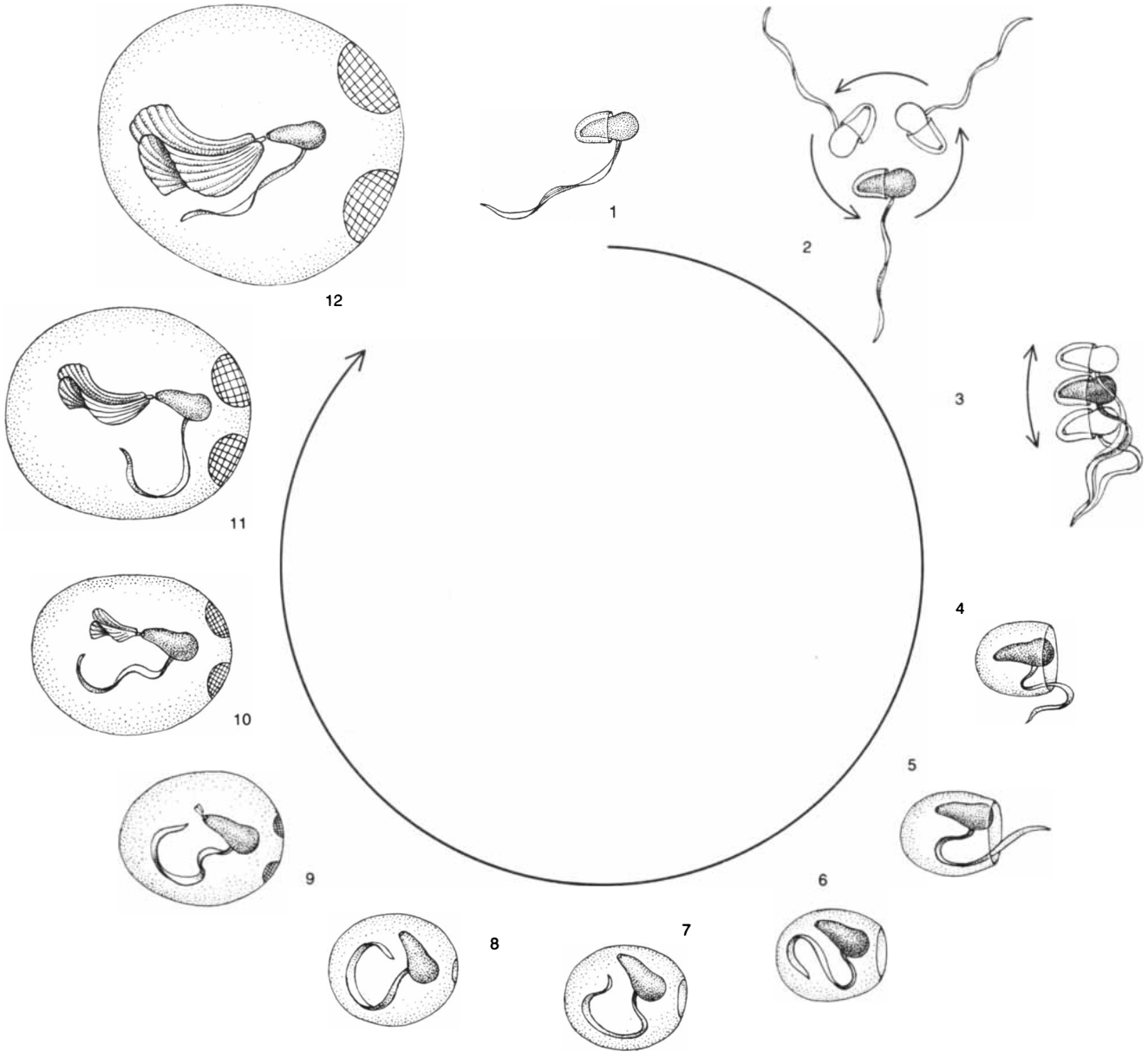
The feeding filter is a highly efficient plankton trap, but exactly how the particles are trapped is not known. They may be caught when they adhere to the sticky internal walls of the filter. Alternatively one of the membranes in the sandwich that forms the filter may let water through it but not particles. The water flowing in one direction through such a membrane would leave all the particles trapped on one side.

Once the particles are trapped in the feeding filters the appendicularian ingests them in a truly remarkable way. Once every few seconds the animal sucks the particles off the feeding filter into the median channel and up into its mouth by the action of the cilia in the spiracles on its trunk. The sucking action is analogous to drawing milk up through a straw. The particles that are carried into the animal's mouth are then collected by a feeding mechanism that is common to all the tunicates, including the sedentary ascidians: the endostyle near the mouth forms a thin, porous mucus funnel that lines the pharynx and extends into the stomach. The water entering the mouth passes through the funnel and out through the spiracles and gill slits into the tail passage of the house. The food particles are trapped because they adhere to the mucus, which is then wound into a thin string and digested in the stomach. Appendicularians can process large amounts of food in a short time. Waste is extruded as a multitude of tiny fecal pellets that can rapidly foul the house and clog the filters. When that happens, the appendicularian abandons the house.




**APPENDICULARIANS MAY HAVE EVOLVED from the planktonic larva of a primitive deep-sea chordate (*bottom*), according to a hypothesis put forward by Robert Fenaux. In his theoretical evolutionary sequence the flat tail of the primitive chordate became partially differentiated from the trunk (*second from bottom*). Primitive chordate attained sexual maturity while it was in larval form (*second from top*). Eventually tail completely differentiated from trunk and rotated 90 degrees so that it was flat from front to back, as in modern animal (*top*).**

The mucus that forms the walls and filters of the house consists of a gelatinous material that is secreted on the surface of the trunk by a layer of specialized glandular cells, the oikoplast epithelium. The pattern




**APPENDICULARIAN BUILDS A NEW HOUSE after it abandons the old one. It may build a house several times a day, in a process that takes only a few minutes. While the animal is still in its old house it has already secreted a new one complete with filters and carries the rudiment of it in collapsed form against its trunk. After abandoning the old house the animal intermittently floats and swims for 30 to 120 seconds (*1*). Soon it begins a series of violent cartwheeling (*2*) and nodding (*3*) motions that enlarge the rudiment of the house. The tail is then pulled into the rudiment (*4–8*) in less than a second. The animal enlarges the house even further with a series of sinusoidal vibrations traveling down its tail from the base to the tip. As the house enlarges, opening through which animal entered closes. Meanwhile the feeding filter expands (*9–11*). When both the house and the feeding filter reach their normal size, the animal can begin feeding (*12*).**

of this epithelium, the outer membrane of the animal, is characteristic for each species and determines the structure and shape of the house. Different groups of cells can manufacture mucus of different density and elasticity, so that on expansion the mucus takes a variety of shapes that contribute to the complexity of the resulting structure. In the Oikopleuridae the oikoplast epithelium covers most of the trunk; in the Fritillaridae it is reduced to an area on the upper front portion of the trunk and around the mouth.

The oikoplast epithelium can be divided into regions based on the types of cells present and the parts of the house that are made there. One region of specialized cells, known as Eisen's oikoplast, is responsible for making the mesh covering over the incurrent openings of the house. Another region, Fol's oikoplast, produces the feeding filter. The species *Oikopleura longicauda* is unique in the family Oikopleurida in that it lacks Eisen's oikoplast; thus its house has no mesh over the water inlet.

The construction of a new house by an appendicularian begins with the secretion of gelatinous material by the oikoplast cells. The mucus accumulates in a layer at the top of each cell just under the cell membrane. A new membrane is then fabricated directly under the mucus layer, moving the mucus to the outside of the cell. There the mucus coalesces into the rudiment of a house. Special structural fibers are manufactured by both Eisen's and Fol's oikoplasts. Although the secretion of a house may take as long as four hours, some species, such as *Oikopleura cornutogastra,* can secrete one in five minutes.

After secretion the animal's trunk is covered with a thin gelatinous film, which is carried on the trunk in collapsed form until a new house is needed. The shape and final form of the house have been determined at the time of its secretion. The rudiment is now ready to be expanded.

The animal expands its new house only after it has abandoned or discarded the old

one because the filters have become clogged with phytoplankton and detritus. It may also discard the house when it is threatened by a predator such as a fish larva. Appendicularians build houses with amazing frequency. Most of the species that have been studied secrete and expand a new house every four hours. When *Oikopleura rufescens* is disturbed in a collecting jar, it may build as many as three houses in 30 minutes. The house of *Oikopleura albicans* is reported to have a special hatch through which the animal can escape. Most species escape, however, simply by moving their tail vigorously and physically forcing the walls of the house apart.

The secretion of a house must require considerable energy. Members of the family Oikopleurida have developed a mechanism to unclog the incurrent filters, thus postponing the need to abandon the old house: they momentarily suspend the beating of their tail and reverse the flow of water with their ciliated spiracles. The water flowing out through the incurrent openings unclogs the filters by sweeping away the large particles trapped there.

Once the old house is discarded, however, the free-swimming animal begins immediately to expand the new one. It swims intermittently with a jerky motion for several minutes. During this period the collapsed rudiment of the new house expands slightly into a capsule that fits like a glove around the front end of the trunk. The animal then begins a series of violent movements to wriggle partially out of the house rudiment. Rapid sinusoidal motions of its tail often make it cartwheel or nod its head back and forth. The nodding pulls the trunk away from the encompassing house rudiment. When the rudiment is sufficiently expanded, the animal pulls its tail into the house, base first and tip last. It is now completely surrounded and cramped in the tiny house, its tail in the shape of a question mark with the tip touching the animal's "nose." Small sinusoidal motions of the tail, beginning at the base and traveling to the tip, draw water in through the incurrent filter and slowly expand the house. The house grows larger around the animal as water is pumped into it. The expansion may take several minutes, during which the open rear end of the house through which the animal entered gradually closes. When the house attains its full size, water can pass completely through it, and the animal begins its normal feeding.

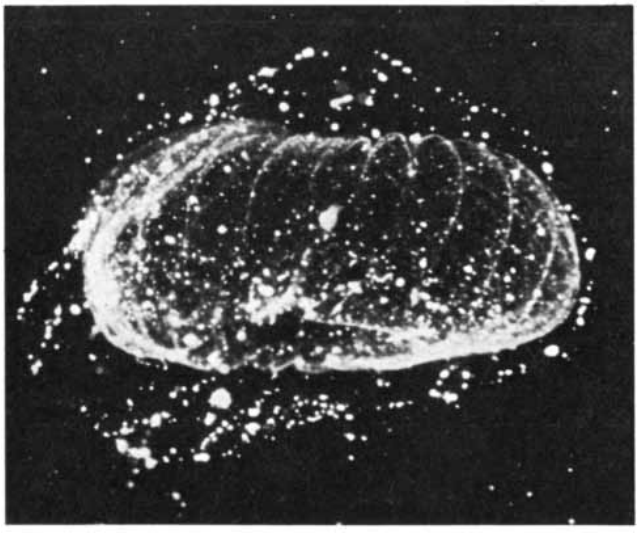
Since appendicularians are among the few multicellular organisms that are capable of feeding on nanoplankton, they hold an unusual and important position in the food web of the open ocean. As many as 50,000 phytoplankton cells may be trapped on a single appendicularian house at any one time. The entire structure and function of the house are adapted to maximize its filtering efficiency. G. A. Paffenhofer of the University of Georgia has recently raised *Oikopleura dioica* through 19 generations in his laboratory. He found that the larger members of that common and relatively small species could remove all the phytoplankton from 300 milliliters of seawater per day—more than 250,000 cells! My own observations suggest that the larger species such as *Megalocercus huxleyi* and *Stegosoma magna* filter several hundred milliliters of seawater per hour.

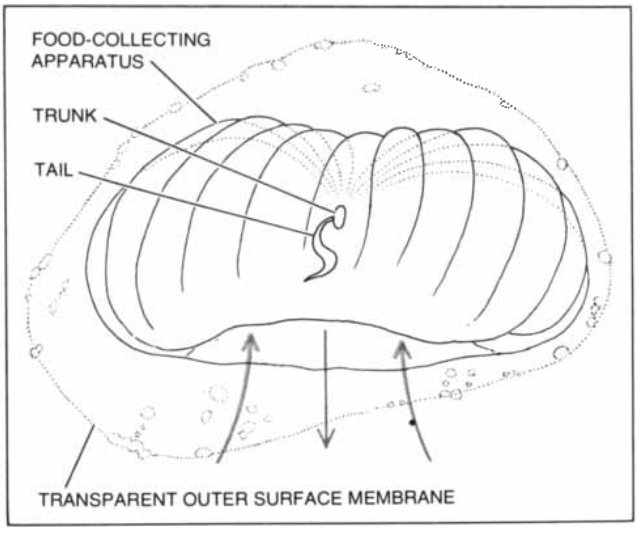
In areas where appendicularians are abundant they may drastically reduce the quantity of phytoplankton available to other planktonic herbivores. Even if the appendicularians do not consume all the particles they filter, they substantially alter the form of the food. Normally phytoplankton are highly dispersed. In the course of collecting the phytoplankton the appendicularians concentrate them in mucus packages, thus making them unavailable to other filter feeders.

Appendicularians are an important link between the nanoplankton and the larger animals of the oceanic food web, both planktonic and neritic (large, actively swimming organisms such as fishes). Their major predators include the larvae of herring, sardines and flatfish. The larva of the plaice, a flatfish, may consume 25 or 30 small larval appendicularians per day. The sergeant major, a common yellow and black striped reef fish, often feeds on appendicularians. Since the particle-covered houses are frequently much more obvious than their transparent inhabitants, animals that seek their prey visually may actually see the house rather than the animal within and consume both together.

Jellyfishes, chaetognaths (arrowworms) and siphonophores (smaller relatives of the surface-dwelling Portuguese man-of-war) also feed on appendicularians. These planktonic predators are a great hazard to an appendicularian that is between houses and is hence not protected by its shield of mucus. At times, however, a disturbed appendicularian will desert its house and rapidly swim away, leaving the house as a decoy for a predator. Species that build particularly elaborate houses, such as *Oikopleura rufescens,* have invested large amounts of energy in the house and do not readily abandon it. The houses of these species may be poked and bounced around considerably before their occupant will desert them.

Although the appendicularian proper is






**HOUSE OF THE FAMILY KOWALEVSKIIDA is particularly fragile and rare. Until recently only one such house had ever been described (by the zoologist Hermann Fol in 1872). This photograph by King is the first ever made of one. The house is shaped like an umbrella; the animal itself is the small white spot in the center. The movement of the animal's tail draws water into the house along the ribbed inner walls, where particles of food are collected. The water passes out of the house in the center of the opening through which it entered. The path of the water is indicated by gray arrows, the path of food by colored arrows. The house shown is about the size of a five-cent piece.**

# Western Electric Reports:

## Batch bonded crossovers bridge the gap.

A thin-film integrated circuit may be thought of as a road map on which active electronic components (the towns) are linked together by conducting paths (the roads).

In a simple circuit, these paths can be laid out on the same plane. But as circuit complexity increases, some conducting paths must span others in bridge-like constructions that are called crossovers.

Engineers at Western Electric's Engineering Research Center in Princeton, N.J., have developed an improved method for simultaneously constructing thousands of crossovers on a single circuit. In addition to lowering manufacturing costs, the new technique has given Bell Labs engineers even greater freedom in designing thin-film circuits.

Until recently, most crossovers were plated directly on a patterned ceramic circuit board. But plated crossovers are very delicate. And unrepairable defects mean that a relatively expensive patterned circuit board has to be discarded.

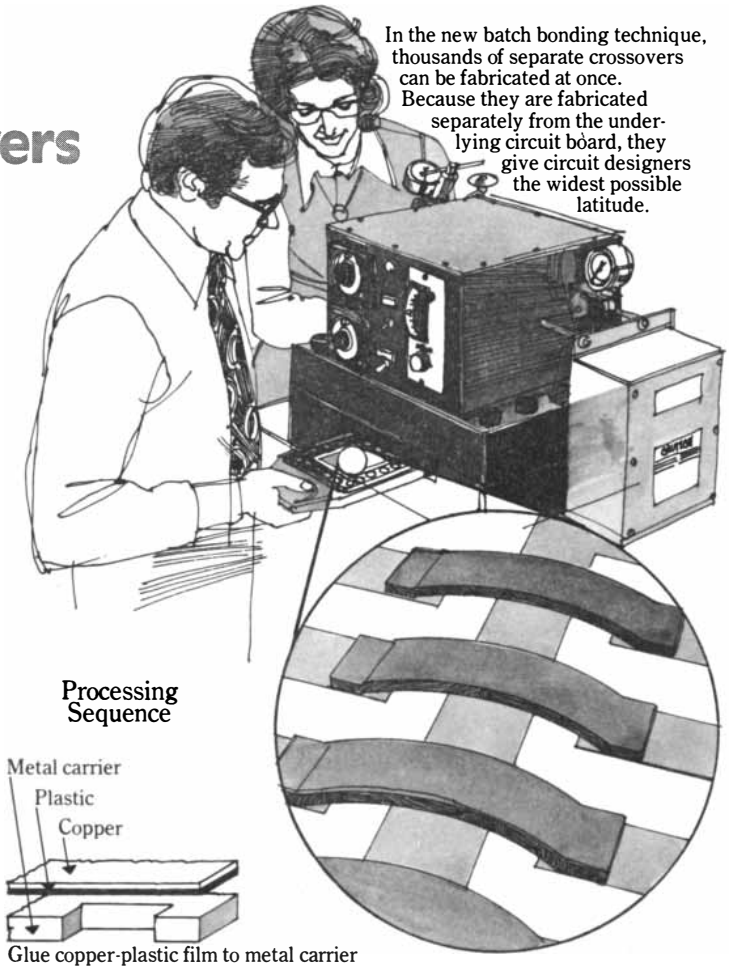
In the new batch bonding technique, an array of crossovers is fabricated on a separate film. They are transferred to a patterned circuit board only after inspection has assured the array is good.

A reusable metal sheet with tiny slits at the desired crossover locations is basic to the new technique. A copper-plastic laminate is glued to the metal sheet with the plastic side against the metal surface. Short, narrow gold lines are electroplated onto the copper side in registration with the slits in the sheet. The copper not gold plated is etched away, leaving an array of gold-plated copper lines on the plastic film.

Applying pressure to this array with a rubber pad forms the gold lines into tiny arches, by pushing them slightly into the openings in the metal sheet. After inspection, the entire array of good arches can be bonded to a patterned thin-film circuit board.

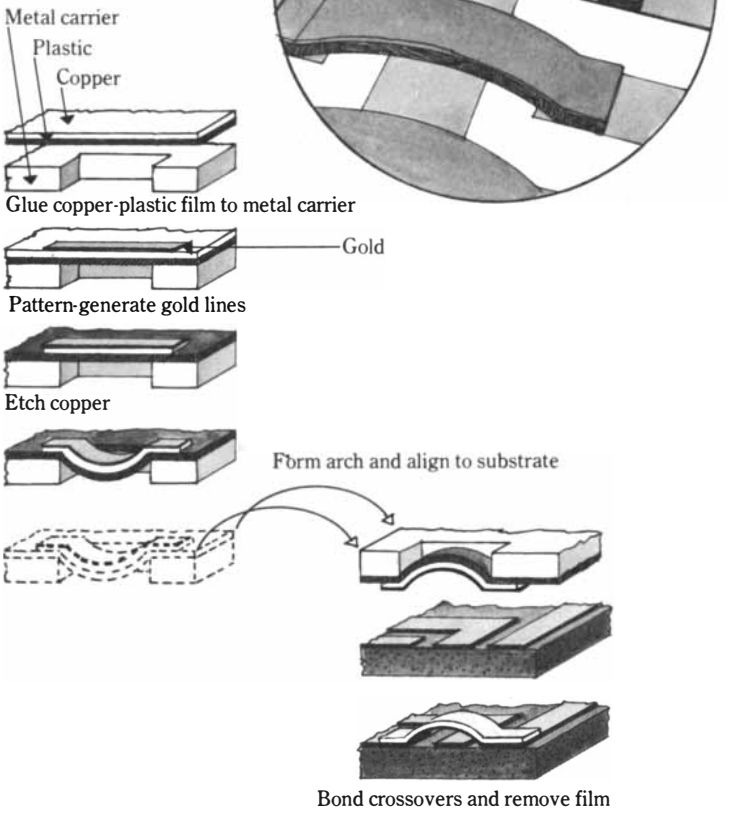
**Benefit:** Batch bonded crossovers are one more manufacturing innovation that allows the Bell System to meet your communication needs reliably and economically.

For more information, send a large, self-addressed envelope with 24¢ postage affixed to: Advertising Manager, Western Electric, Room 1626, 195 Broadway, New York, N.Y. 10007.



In the new batch bonding technique, thousands of separate crossovers can be fabricated at once. Because they are fabricated separately from the underlying circuit board, they give circuit designers the widest possible latitude.

Processing Sequence



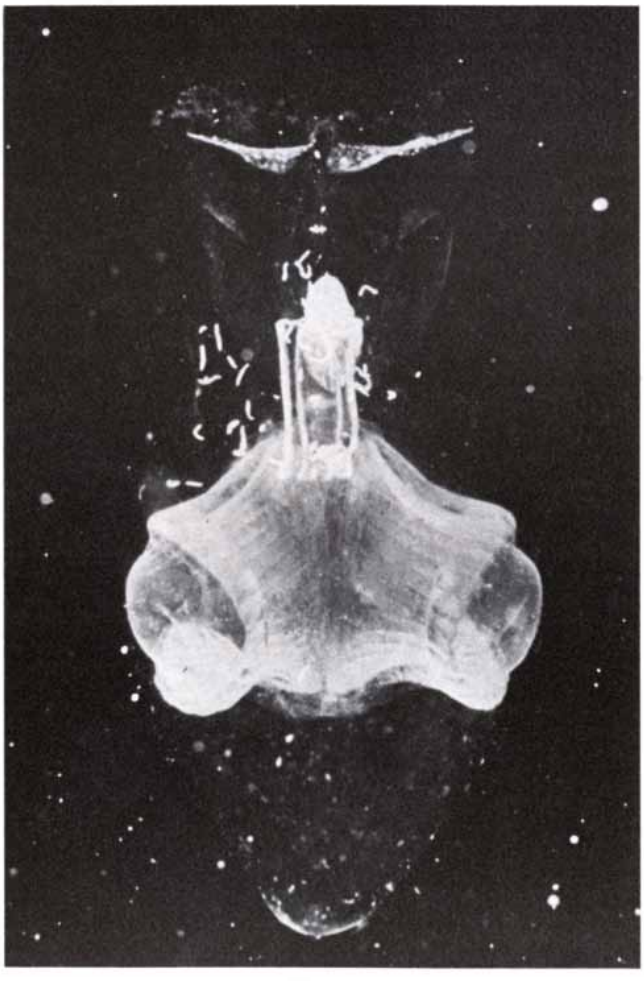

Western Electric

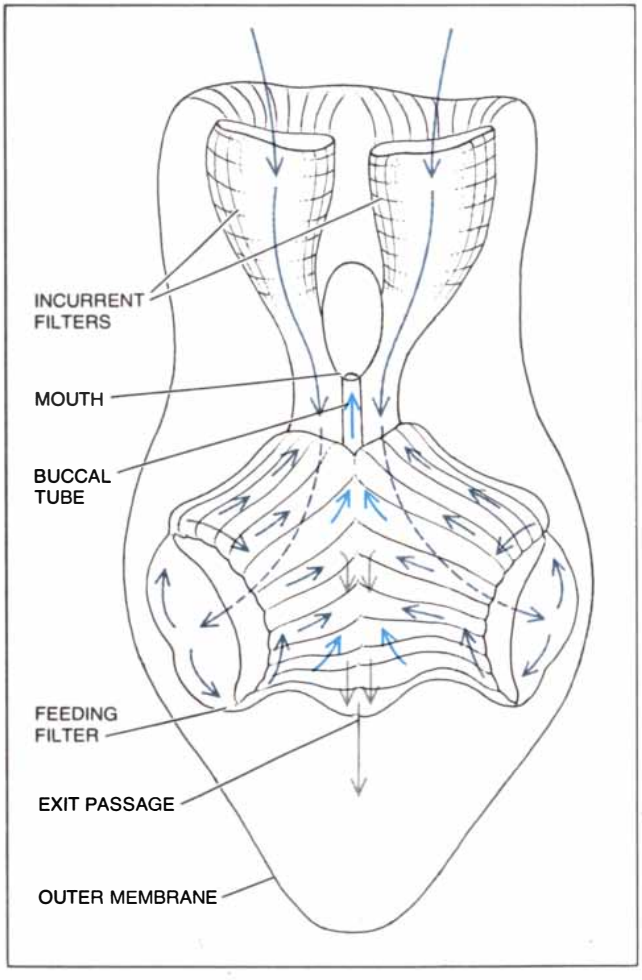
an important link in the oceanic food web, the discarded houses may have an even greater impact on plankton ecology. A few appendicularians, each manufacturing perhaps six houses per day, can quickly saturate the surrounding seawater with their cast-off mucus dwellings. In areas where the animals are abundant discarded houses often reach a density of several hundred per cubic meter. Scuba diving among them is like swimming in a snowstorm.

Each discarded house is a concentrated package of phytoplankton, mucus and detritus, a rich food source in an environment where normally food is highly dispersed. Many kinds of zooplankton, including some copepods, euphausiid (krill) larvae, flatworms and polychaete-worm larvae, have been observed resting on the surfaces of discarded houses and grazing on the mucus and the particles trapped in it. The mouthparts and feeding appendages of these organisms are adapted to scraping rather than to filter feeding. The organisms that feed on appendicularian houses therefore exploit a source of food (the nanoplankton) they are not adapted to gathering by themselves. Fish feeding on occupied houses may also utilize the nanoplankton. It is in this way that the appendicularians' unusual feeding structure serves as a link between the nanoplankton and many organisms to which such phytoplankton are not normally available.

The discarded houses alter not only the form and concentration of phytoplankton but also the structure of the planktonic environment. The word plankton normally conjures up an environment where tiny plants and animals float without hindrance in a totally fluid medium. Although the planktonic organisms may bump into one another, only at the bottom do they encounter a solid physical substrate. Observations in the open ocean by divers and from submersible vehicles, however, have revealed an abundance of macroscopic organic aggregates, sometimes referred to as marine snow because of their resemblance to drifting snowflakes. These aggregates may reach a diameter of several centimeters. Some are formed from material that has been deposited on small particles through a variety of processes, including bacterial action. Many, however, are the discarded and decomposing mucus by-products of various zooplankton, particularly the pteropods, the salps, the planktonic tunicates closely related to the appendicularians, and of course the appendicularians themselves.

These large, amorphous bits of mucus and detritus serve as surfaces on which many planktonic organisms can rest or feed. Bacteria and protozoans use them as a permanent habitat. Appendicularian houses and other particles of marine snow provide tiny solid substrates and introduce heterogeneity into an environment that is generally considered to be relatively homogeneous physically. Although these miniature habitats have not been completely explored, it is certain that they have influenced the adaptations and feeding strategies of many planktonic organisms.






**HOUSE OF MEGALOCERCUS HUXLEYI, a species in the family Oikopleurida, has an unusual torpedo shape. Water pumped by the animal's tail flows into the house through two cone-shaped filters. It then travels down a tail passage and diverges into two cylindrical passages leading to the feeding filter. The water, laden with food particles, enters the feeding filter at two points at the base of each wing of the filter. Particles collected on the membranes of the feeding filter are carried into the animal's mouth by the buccal tube. Filtered seawater leaves the house at the rear with enough force to propel the house forward with an erratic corkscrew motion. The flimsy outer membrane of the house is visible only at the rear end in the photograph. The house of this species may reach several centimeters in length.**

# Alas, we have too few new Isuzu's.

See, what with the long boatride from Japan, and the careful way they put the little rascals together over there, Opel Isuzu's aren't exactly flooding into the country. Actually, right now it's more like a trickle.

And that's a pity. Because once people start seeing them, and driving them, we think they're going to be all the rage.

Because what Opel Isuzu offers, very simply, is a lot of car for the money.

It comes standard with reclining bucket seats. Flow-through ventilation. Tinted glass. Rack and pinion steering. Front disc brakes. A short-throw, four-speed transmission. And a sophisticated little 1817 cc overhead-cam hemi engine. With cross-flow heads and five main bearings.

As if that weren't enough, you can order an automatic transmission. Radial tires. Air conditioning. A console full of gauges. All sorts of stuff.

And with the standard engine and transmission, Isuzu works the bejabbers out of a gallon of gas. According to EPA tests, an Opel Isuzu is rated at an estimated 23 mpg in the city. And 36 on the highway.

Of course, the actual mileage you get will vary depending on how and where you drive, the condition of your car, and how you equip it. Which is as you might expect.

You want one already, don't you? Of course you do.

Well, if you promise to come right over, your Buick Opel Isuzu dealer will try to fight the Isuzu crowds off until you arrive.

But do try to hurry. They can only hold out just so long.

**OPEL ISUZU**

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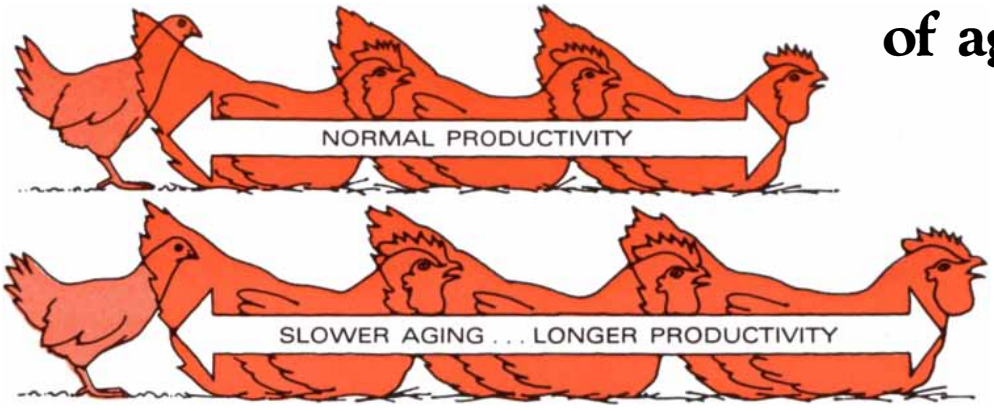
MARK OF EXCELLENCE

# Santoquin® Antioxidant (ethoxyquin) can it actually slow the process of aging?




It's a question that could hardly have arisen at a busier time for the molecular biology group of Monsanto's Research Dept. For one thing, a pressing series of studies are afoot on the company's Polaris®, a higher sugar-producing treatment for ripening cane. The studies are trying to unravel the exact biochemical mechanism of *why* the compound can promote up to 15% more sucrose in the harvest. Is it the effect on invertase level? Why is there less response when ripening conditions approach the ideal?

In the middle of it, this intriguing aging question has arisen, too important to be set aside.

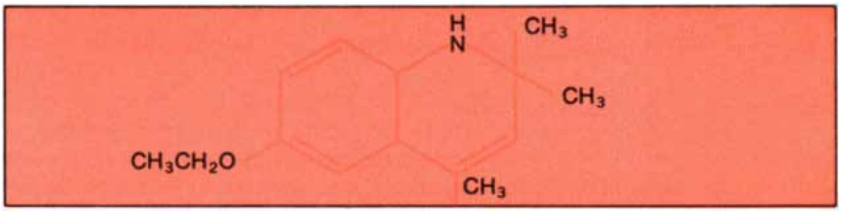
Is it possible that the company's well-established and long-commercialized Santoquin® feed antioxidant has this unexplored effect? The ability to *slow* the aging process in living bodies would include poultry, and that could perhaps be a way to prolong the producing life of chick breeders and laying hens. The same age-delaying mechanism might extend the siring virility of top-of-breed horses, bulls and boars and stretch out the milk-giving period of dairy cows. It might give pet dogs and cats a longer lease on life.

The published studies to date on slowing the aging process with antioxidant ingestion are scarcely definitive. There's too little data to show that it will, but too much to say that it won't. Yet the research programs necessary to check all this out will take a long, long time.

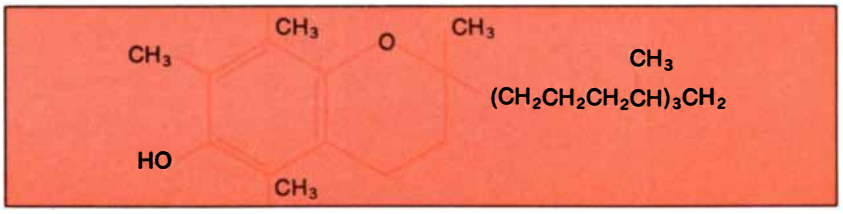
Nevertheless, in the struggle to produce more food, no by-way can be left unexplored.

### So Different, So Alike

Santoquin antioxidant, more familiar as a commonly-used feed ingredient by its generic nickname of ethoxyquin, is feed-grade: 6-ethoxy-1,2-dihydro-2,2,4 - trimethylquinoline. The structural formula looks like this:




One of the most familiar (and perhaps important) antioxidants that Mother Nature provides living bodies is Vitamin E. Its most potent isomer, -tocopherol, looks like this:




There's no resemblance at all.

Yet despite this difference in structure, Santoquin antioxidant acts *like Vitamin E in all known metabolic functions!* One of its most pronounced effects is to inhibit the formation of peroxides during the processes of digestion and metabolism.

The evidence which has been accumulating that ethoxyquin may slow down aging does not come from the highly enthused "mega" vitamin sector. It comes from published papers that report some solid research by eminent biochemists, biologists, chemists and gerontologists.

Monsanto's own research with feeding tests has also provided some supportive evidence, but purely from *chemical* and *feed-response* standpoints. Sadly, in all the work done to date, none has been focused on delving into this potential "aging inhibition" property.

But the chemical evidence plus the *in vivo* studies that have surfaced from various sources are too suggestive to shrug off.

### Tantalizing Evidence

In a most erudite paper, *Aging At The Cellular Level,* Dr. B. L. Strehler cited twenty-three research models compiled by the Association for The

Advancement Of Aging Research. Of the physiological enigmas listed, a preponderance of the biochemical changes associated with aging *could* be triggered by or be the direct cause of *oxidation* in body tissues.

A number of eminent researchers – Mrs. Denham Harman, William A. Pryor, and Johan Bjorksten among them – have offered evidence that the existence of free radicals in the body and cross-linking of various biomolecules are a significant factor in the aging process. Bjorksten, in over a quarter century of study, has reported comprehensively in books and papers on the subject. Pryor, too, has deeply investigated free radical propagation reactions and defined five types. The mode of occurrence of two of these and their possible biochemical effects was reported in *Chemical & Engineering News*, Special Feature Article, published June 7, 1971. This paper also examined the possible role of chemically-made antioxidants and Vitamin E in the aging process.

In a talk on the subject of "Free Radical Theory of Aging" at the 19th Annual Meeting of the Gerontological Society, Dr. Denham Harman symbolized the free radical reaction of oxygen with biomolecules in this fashion:

| | | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Initiation: | RH | + | $O_2$ | $\xrightarrow{Cu}$ | R· | + | $HO_2$· | |
| Propagation: | R· | + | $O_2$ | → | $RO_2$· | | | |
| | $RO_2$· | + | RH | → | R· | + | ROOH | |
| Termination: | R· | + | R· | → | R:R | | | |
| | R· | + | $HO_2$· | → | ROOH | | | |

He pointed out that the rate of reaction of propagation and ultimate chain-length of cross-linking depend on the number of times the propagation step is repeated, i.e. the incidences of free radical promoters and amounts of available oxidants, which would include peroxides.

### One Clue – Highly Specific

In another talk at the 4th Annual Meeting of the American Aging Association, Sept. 1974, Eddy and Harman demonstrated the inhibiting effect of antioxidants in the diet on a specific phenomenon of aging: the formation of amyloid, a constituent of senile plaques – frequently referred to as aging pigments. In this report, it was stated that casein-induced amyloidosis in mice subjects was reduced from 65% to almost zero by diets containing 0.25% of two different synthetic antioxidants, with Santoquin (as one) having the somewhat greater effect.

Although the work was directed at amyloid formation, data was also cited that showed the pronounced beneficial effect on the mice's mortality rate by adding Santoquin antioxidant to the diet. Without the antioxidant in the diet, 20% survived to 18½ months; on diets with 0.2% Santoquin, 20% survived for 23 months.

This was not the first intimation of increased longevity by any means. As early as 1966 and again in 1970, Dr. Harman demonstrated that by feeding weaned mice on diets containing 0.5-1% antioxidants the life span was increased 30-45%. He reported that in human terms this equated to a life expectancy of about 100 years.

### Are Free Radicals The Chief Culprits?

There has come to light a ponderous amount of data that shows (a) that free radical scavengers can have a critical role in slowing aging, (b) that inhibiting systemic oxidation DOES counteract certain effects of aging, and (c) that Santoquin antioxidant is highly effective in countering this kind of biochemistry.

Monsanto's research (and others as well) has amply proved that Santoquin antioxidant decreases the uptake of oxygen by unsaturated fats and prevents formation of organic peroxides in the bird and animal body. As a consequence, the recommended 125 ppm level of Santoquin in poultry feeds delays the breakdown of nutrients (vitamins, amino acids, pigment formers) in the diets and thereafter protects against loss throughout digestion and metabolism. This protection against free radical degradation thereby enables the animal to get more good out of the feed. In brief, there is no question that Santoquin does indeed scavenge free radicals in the animal system. As does Vitamin E. This was demonstrated early by feeding studies that showed Santoquin could fully protect poultry from the onset of encephalomalacia, an E-deficiency syndrome, even on diets from which all natural Vitamin E had been removed.

### No Quick Answers

What's Step One? Free radicals have already been shown to have a causative relation with the aging process. Santoquin antioxidant has been shown to scavenge free radicals, to inhibit formation of peroxides and its presence definitely slows down the oxidation of unsaturated oils and lipids. How can this effect be checked out against chickens, pigs, milk cows and pets?

In a small group-think session, one of Monsanto's cellular biology specialists pointed out a basic approach that would provide the first clue. When normal living cells are taken from an animal embryo and raised in a culture medium – they replicate a specific number of times, then die. The life span of the cell culture and number of replications are *specie specific* and correlate with that animal's life span. If the presence of ethoxyquin in the culture lengthens the life span or increases the number of perfect replications. . . ?

But that would be only a clue. It would still have to be checked out on whole living animals.

Breeding swine normally live 12-15 years; milk cows produce for 7-10 years; a stud horse is still going strong at 30! Rats and mice who give up the ghost at 2-3 years can't help; their metabolism of nutrients is radically different and pretty much their own. Any way you look at it – the final check-out – is going to take a long, long time.

It looks most logical from a pragmatic standpoint to start with laying hens. Their productive life is shorter, a mere 2-3 years. And egg laying drops off as they age. But any effect here would at least mean more eggs per hen!

*For more information on Santoquin antioxidant in published studies on aging effects, request a copy of:* Antioxidants in Feeds & Observed Effects on Aging.

Address:
Dr. G. L. Romoser B2SF
Monsonto Company
St. Louis, Missouri 63166
TEL.: (314) 694-2765

**Monsanto the science company.**

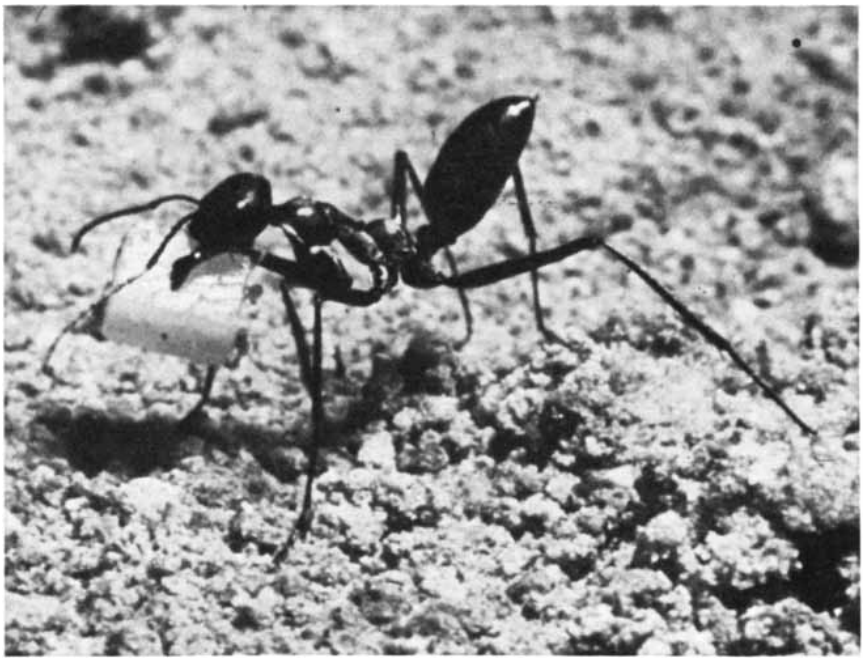
# Polarized-Light Navigation by Insects

*Experiments demonstrate that bees and ants find their way home by the polarization of the light of the sky. The detection system insects have evolved for the purpose is remarkably sophisticated*

by Rüdiger Wehner

The eyes of insects are sensitive to a natural phenomenon that man is blind to: the polarized light of the daytime sky. It is this capacity that underlies the remarkable navigational ability of many insect species. Exactly how can an insect navigate by polarized light? To ask this question is really to raise three separate questions: What makes the visual cell of an insect sensitive to polarized light? How do some minimum number of visual cells cooperate to determine the direction of polarization at one point in the sky? How much information from how many points in the sky does the insect need for unambiguous navigation?

The light radiated by the sun is unpolarized, that is, its waves vibrate in all directions at right angles to the line of sight. In traveling through the earth's atmosphere, however, it is scattered by molecules and other particles that are small with respect to the wavelength of light, so that at each point in the sky its waves tend to vibrate in a specific direction. This atmospheric polarization was first described by Lord Rayleigh in 1871, but it was not until 1950 that it was given a full theoretical analysis by S. Chandrasekhar of the University of Chicago. More recently a computer analysis has been developed by Zdenek Sekera and his colleagues at the University of California at Los Angeles. Their program makes it possible to specify both the directions and the degrees of polarization for all points in the sky, for different atmospheric conditions and for spectral wavelengths ranging from the infrared to the ultraviolet.



**LONG-LEGGED ANT (*Cataglyphis bicolor*) of the North African desert was used by the author and his students in their studies of polarized-light navigation by insects. The ant forages until it finds food and then runs straight back to its nest. It can be trained for experimental purposes by rewarding it with a small piece of cheese. This ant holds cheese in its mandibles.**

The pattern of polarization in the sky varies with the position of the sun or, more exactly, with the orientation of the plane of a triangle formed by the sun, the observer and the point observed [*see top illustration on page 109*]. At any point on the celestial sphere the direction of polarization is always perpendicular to the plane of such a triangle. By disregarding a few exceptions and applying this general rule to all points in the sky one can determine the entire pattern of polarization for any given position of the sun.

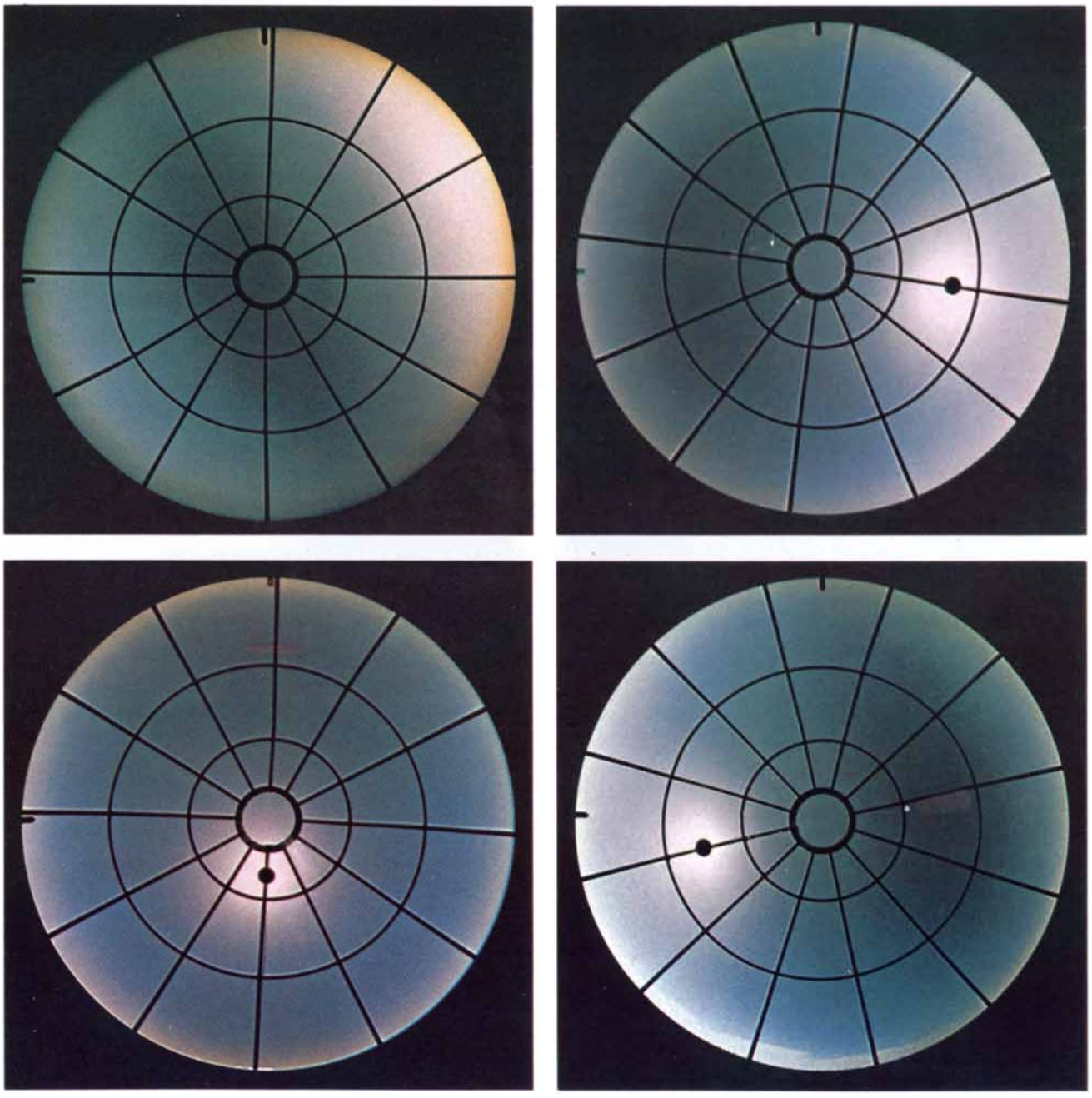
The general rule for the polarization of light by the atmosphere is easily demonstrated by making photographs of the sky with a 180-degree "fish-eye" lens fitted with a polarizing filter. Consider a pair of photographs that are taken just as the sun reaches the horizon [*see upper illustration on page 108*]. When the polarizing axis of the filter is parallel to the solar meridian (the arc connecting the sun and the zenith), a broad dark stripe runs across the celestial hemisphere at right angles to the solar meridian; the center of the stripe is 90 degrees away from the sun. When instead the polarizing axis of the filter is perpendicular to the solar meridian, no such stripe is evident. The presence of the stripe in the first instance is a function of the direction of skylight polarization at sunrise and sunset; the maximum polarization is found 90 degrees away from the sun. The pattern of polarization shifts around the celestial hemisphere as the sun moves across the sky; this too can be documented by successive fish-eye-lens photographs.

The ability of honeybees to navigate by the polarized light of the sky was first described some 25 years ago by Karl von Frisch. His finding came as a surprise; even though the polarization of skylight had been known since the 19th century, no one had really considered the possibility that the phenomenon could serve any navigational purpose. It has recently been learned, however, that about the year 1000 the Vikings were taking advantage of the polarization of skylight in their voyages west from

Iceland and Greenland to Newfoundland. The Danish archaeologist Thorkild Ramskou has pointed out that the "sunstones" described in the old sagas were nothing other than birefringent and dichroic crystals that could serve as polarization analyzers.

As I write this article I have on my table a small crystal of cordierite. When I look through it at any point in the sky, I can determine the direction of polarization by observing the changes of color and brightness as I rotate the crystal around the line of sight. Some years ago an airplane was steered with fair precision from Norway to Sondre Storm Fjord airfield in Greenland with a cordierite crystal as the only navigational aid. These crystals can be found as pebbles on the coast of Norway. Although it is unlikely that the Vikings knew anything about polarized light, they apparently perceived the relation between what they saw through a sunstone and the position of the sun (which was often hidden by clouds in those northern latitudes).

There are no polarizing crystals in the eye of insects. The eye of the members of another major group of arthropods—the now extinct marine trilobites—did have hundreds of lenses consisting of the highly birefringent crystal calcite, but the crystals were arranged in such a way that they could not have acted as polarization analyzers. Of course, that does not exclude the possibility that the trilobites were able to use the polarization of skylight for orientation in their marine habitat; Talbot H. Waterman of

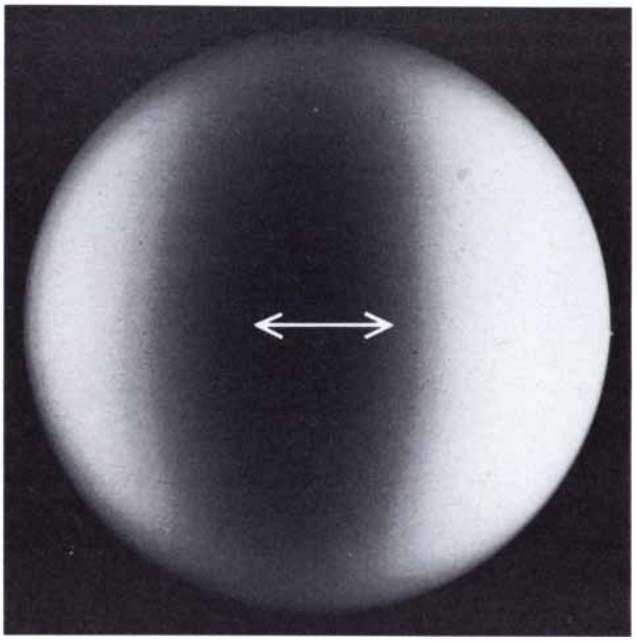


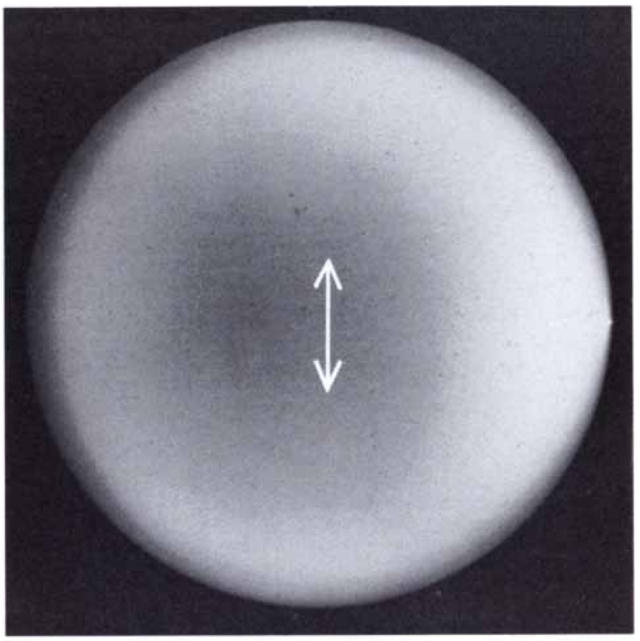
**CHANGE IN THE POLARIZATION** of the light of the sky at different times of the day is shown in this sequence of photographs made with a 180-degree "fish-eye" lens and a polarizing filter. The photographs, made on May 17, 1975, near Kairouan in Tunisia, were exposed at 5:15 A.M. (*top left*), 9:05 A.M. (*top right*), 12:30 P.M. (*bottom left*) and 3:40 P.M. (*bottom right*). A small black screen masks the sun in all the photographs but the first one; the screen also identifies the solar meridian. The axis of the polarizing filter was parallel to the solar meridian in all four photographs. At dawn maximum polarization (*dark region*), located 90 degrees from the sun, is centered in the sky. After sunrise the dark area shifts to the west. At the sun's maximum elevation in the southern sky the dark area shifts to the north; as the sun descends the dark area shifts around to the east. The two marks that appear on the horizon in the photograph indicate north and west.

Yale University has shown that the skylight visible to underwater organisms, like that visible to organisms that live above the water or on land, is polarized. It only means that the lenses were not analyzers located in front of the visual cells. The same is true of insects. Where, then, are the structures in insects that are sensitive to polarized light?

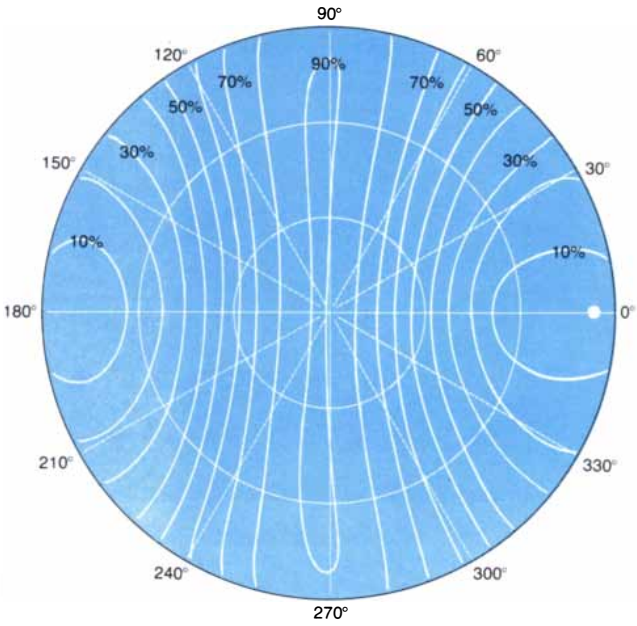
It is now generally agreed that the structures are located within the visual cells themselves. The ability of the visual cells to analyze the axial orientation of the polarized light is the result of a molecular oddity. In all animals, invertebrates and vertebrates alike, the visual pigment rhodopsin is present in the photoreceptor membrane of the visual cells in the form of dipolar molecules, that is, molecules with a distinct axis. As a result the pigment absorbs a maximum of the incoming polarized-light energy when the direction of polarization is parallel to the dipole axis of the molecule.

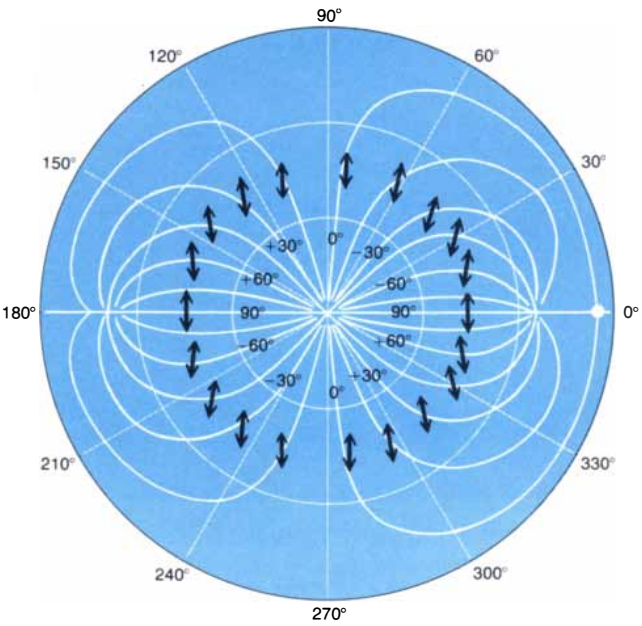
In insects the photoreceptor membranes are bent into arrays of narrow tubes, the microvilli [*see illustration on page 110*]. Timothy H. Goldsmith of Yale and I have come to the conclusion, based on spectroscopic studies we conducted together at the Marine Biological Laboratory in Woods Hole, Mass., that the rhodopsin molecules in the microvillar membrane are preferentially aligned parallel to the axis of the microvilli. Such an orientation would of course result in the maximum absorption of polarized light when, and only when, the axis of polarization coincided with the microvillar axis. (This, incidentally, is part of the reason the human eye is blind to polarized skylight. Among vertebrates, man included, the rhodopsin molecules are free to rotate in the photoreceptor membrane, so that their axial orientation is random. There is an equal chance that any pigment molecule will maximally absorb light with any direction of polarization, and so there is





**MAXIMUM POLARIZATION, demonstrated (*left*) with a fish-eye photograph of the dawn sky, is evident when the transmission axis of the polarizing filter is parallel to the solar meridian. When the axis is perpendicular (*right*), however, variation in intensity disappears.**

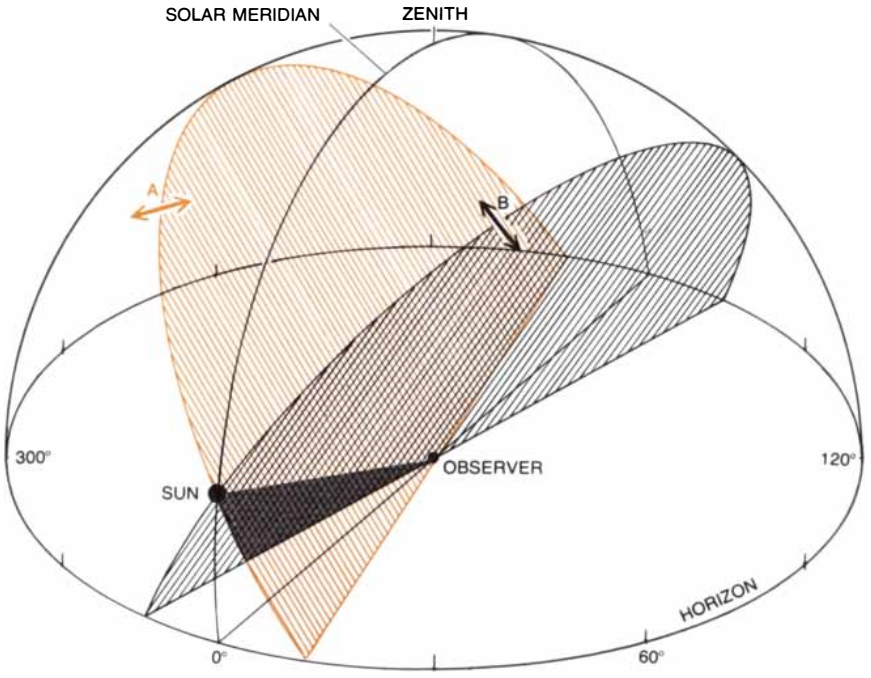



**DEGREE OF POLARIZATION (*left*) and direction of polarization (*right*) at dawn are shown in these graphs of the celestial hemisphere. At the left contours connect points with an equal degree of polarization. At right arrows on contours indicate direction of polarization.**

no particular sensitivity to the polarization of skylight.)

The common orientation of the rhodopsin molecules in the insect's photoreceptor membrane is not in itself enough to allow the analysis of skylight polarization, just as one kind of color receptor is not enough to allow color vision. Different kinds of receptors, each maximally sensitive to a different direction of polarization, must work together in order to enable the detecting system to provide unambiguous results for any direction of polarization. For example, the system must be proof against confusion arising from fluctuations in mean light intensity, degree of polarization and hue of color. But how many receptors are enough? Here we suspected that the principle of parsimony might apply. The number of receptors could be held to a minimum if only one type of color receptor was involved: the ultraviolet receptor, the blue receptor or the green receptor. If two of these types of receptor or all three contributed to polarized-light analysis, more receptors would have to cooperate and more neural circuitry would be needed. Hence natural selection should strongly favor a system that receives its input from only one type of color receptor. What, then, are the spectral wavelengths involved in the perception of polarized light? This question could be most conclusively answered by behavioral experiments.



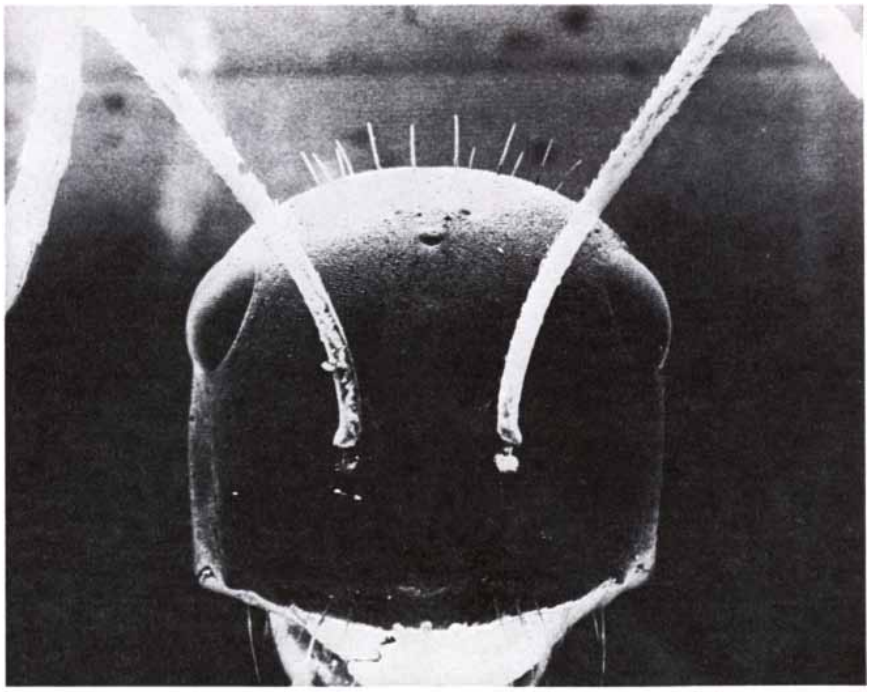

**AXIS OF POLARIZATION (*short two-headed arrows*) of the light of the sky is always perpendicular to the plane of a triangle connecting the observer (*center*), the sun and the point in the sky being observed. The examples shown are for the points *A* and *B* on the celestial hemisphere. The planes of the great circles passing through the sun and each of the two points are hatched. Also shown is the solar meridian: the great circle passing through sun and the zenith.**

Bees are only one of many kinds of insects that have been shown to navigate by the polarization of skylight. Ants also do so, and my students and I at the University of Zurich have used both bees and ants as experimental animals in our studies. In most of our experiments a desert ant native to North Africa, the species *Cataglyphis bicolor,* has been the preferred animal for several reasons. First of all, it is difficult enough to follow a flying bee over any great distance, but to keep a polarizer or any other optical equipment in place above a bee as it flies is impossible. The desert ant is a running forager, but it rarely runs faster than 20 meters a minute, which is less than a mile an hour. This enables the experimenter to record the ant's navigational courses in full detail and at the same time to continuously interpose between the animal and the sky almost any kind of optical equipment.

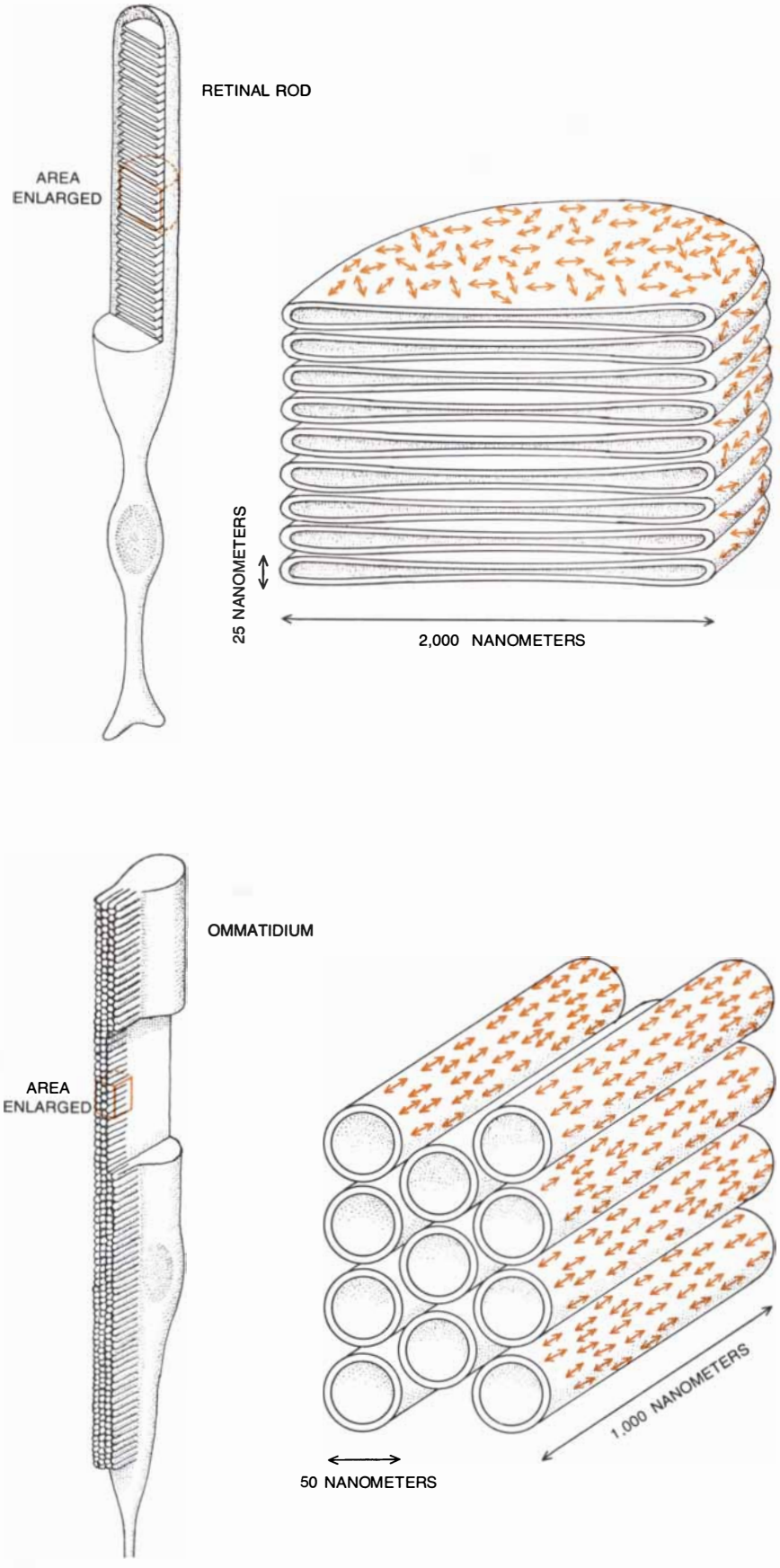
In addition the desert ant is a solitary hunter; it never forages en masse along a scout's scent trail as so many other ant species do. Its desert habitat is notably lacking in conspicuous landmarks, so that the ant must rely almost exclusively on skylight cues to guide it on its forays. A typical *Cataglyphis* excursion of the kind we have often recorded begins when the ant leaves its underground nest. The ant then meanders, covering a distance that may be equivalent to the length of a football field, until it captures prey. After that it runs straight back to the nest.

When I first observed these long-legged ants eight years ago, I was fascinated both by the extraordinary precision of their orientation and by their remarkable learning capacity. Individual ants were easily trained to travel in a given direction for a given distance by rewarding them with a tiny piece of cheese. For experimental purposes we would transport the trained ants to a remote testing area, carrying them in individual lightproof flasks. The testing area, a hard sandy plain, was painted with a grid of fine white lines, a coordinate system that enabled us to record the ants' running courses on a reduced scale for later statistical analysis.

When each trained ant was released, it would set off in the home direction. It



**HEAD OF THE DESERT ANT is seen from the front in this scanning electron micrograph. Projecting upward from the front of the head are the antennae. At the left and right side of the head are the eyes. The fine pattern visible on the surface of the eyes is the ommatidia: the subunits into which the insect eye is divided. Each eye of desert ant is made up of 1,200 ommatidia.**




**VISUAL CELLS of vertebrates (*top*) and invertebrates (*bottom*) differ in arrangement of photoreceptor membrane and orientation of molecules of visual pigment rhodopsin within membrane. In vertebrates axes of rhodopsin molecules (*color*) are randomly oriented; in insects they are parallel to long axis of tubelike microvilli. This maximizes absorption of polarized light.**

would travel the distance to which it had been trained and then start to circle at the place where the nest was supposed to be. (The actual nest might have been more than a mile away, where the ant had been trained.) On its journey back from the releasing point the ant was accompanied by a small vehicle loaded with optical equipment: neutral-density filters, spectral-cutoff filters, polarizers, depolarizers, retardation plates and so on. These and many similar open-field experiments could not have been accomplished without the enthusiastic cooperation of my graduate students. I am particularly indebted to Peter Duelli (who constructed the vehicle and developed considerable skill in piloting it), Immanuel Flatt, Res Burkhalter (who is now working at the Brain Research Institute in Zurich) and Reto Weiler of the University of Munich.

In order to discover what spectral wavelengths were utilized in skylight navigation we forced the running ants to view the sky through filters of various colors. We were surprised to find that their ability to detect polarized light disappeared completely at wavelengths greater than 410 nanometers; those wavelengths include the entire range of wavelengths visible to man. In light of that spectral range the ants ran in random directions. When we extended the spectral range only a little way into the ultraviolet, however, the ants' navigational accuracy was completely restored.

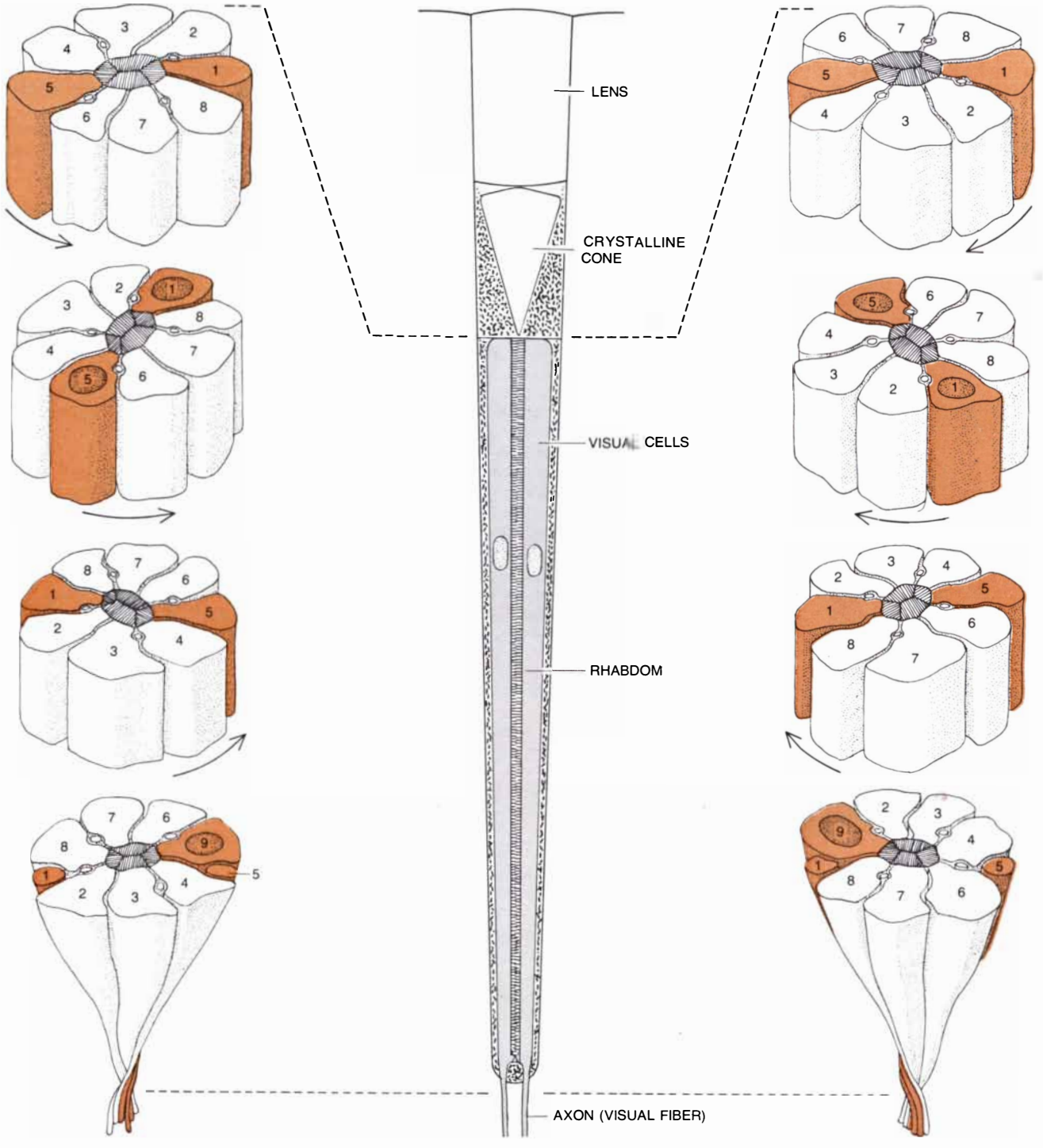
We concluded from this finding that only those visual cells in the ant's eye that are responsive to ultraviolet wavelengths are involved in the perception of polarized light. This can readily be confirmed by comparing the spectral-transmission functions of the filters with the spectral-sensitivity function of the ultraviolet receptor as measured electrophysiologically. Recently Otto von Helversen and Wolfgang Edrich of the University of Freiburg have shown that in bees too the ultraviolet receptors are the only ones involved in the detection of polarized light.

It is easy to understand why natural selection has made the ultraviolet receptors the input channel for an orientation signal. The use of only one type of receptor conforms with the principle of parsimony by holding the input channels down to three, which, as we shall see, is the minimum number. That the type of receptor selected was sensitive to ultraviolet instead of, say, green or blue can be regarded as an adaptation to a purely physical fact: it is in the ultraviolet range of wavelengths that the polarization of skylight is least affected by atmospheric disturbances and is therefore the most stable.

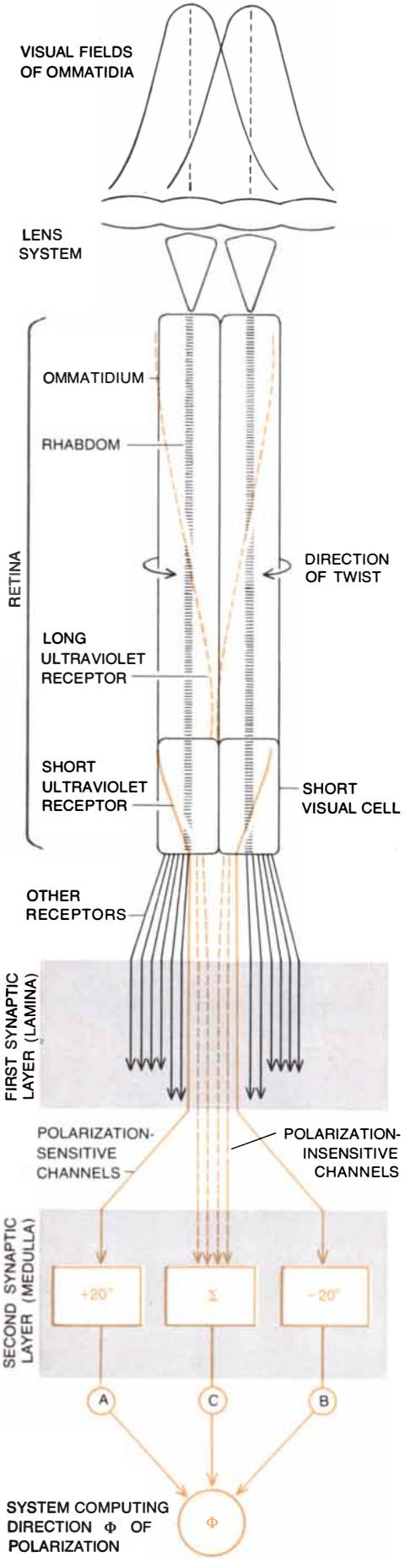
Let us now turn to the second question and consider the insect eye in somewhat more detail. How do the ultraviolet receptors cooperate in detecting polarized light? As is well known, insects have compound, multifaceted eyes. Each eye is composed of hundreds or thousands of the subunits known as ommatidia. Our desert ant's eye

has 1,200 ommatidia; a worker bee's eye has 5,500. Each subunit has its own lens system, and underneath the lens are elongated visual cells that contain the densely packed tubular microvilli where the rhodopsin molecules are located. The microvilli are arranged so as to meet and form a central structure, the rhabdom, which functions as a light guide [*see illustration below*].

There are nine visual cells in each ommatidium. Eight of them are elongated and the ninth is foreshortened. Thus whereas the microvilli of the eight long cells contribute to the rhabdom along its total length, the contribution of the short ninth cell is confined to the lower end of the structure. From a number of independent electrophysiological and neuroanatomical studies one can draw the conclusion that in bees and ants three of the nine cells in each ommatidium are ultraviolet receptors: the




**EYE OF THE HONEYBEE is made up of some 5,500 ommatidia, each consisting of nine visual cells and an overlying optical apparatus: a lens and a crystalline cone (*center*). Eight of the visual cells are elongated; the ninth is short and is confined to the base of the ommatidium. All nine of the cells are twisted. Half of the ommatidia in the bee's eye are twisted clockwise and half are twisted counterclockwise (*left and right*); the two kinds of ommatidium are randomly distributed. The microvilli, which are distributed along the inner edge of each cell, jointly form a central structure, the rhabdom; its membranes incorporate the rhodopsin molecules. Because two of the three visual cells that are sensitive to ultraviolet radiation (*color*) are twisted 180 degrees their preferential sensitivity to polarized light has been lost. The third cell, however, is the short cell; since it is twisted only about 40 degrees, it has retained sensitivity to polarized light.**




short receptor and two of the long ones. Among the workers who contributed to this conclusion are F. G. Gribakin of the U.S.S.R. Academy of Sciences, Randolf Menzel and Allan W. Snyder of the Australian National University, Hansjochem Autrum and Gertrud Kolb of the University of Munich and ourselves at the University of Zurich. Of particular note was Menzel's demonstration by intracellular recordings that the short visual cell of bees is an ultraviolet receptor.

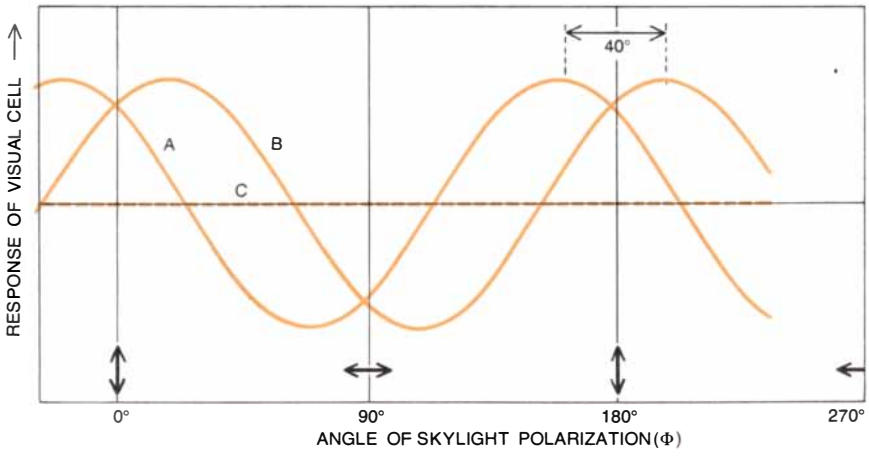
We had started with the assumption that the most elegant system for the perception of polarized light would involve only one type of color receptor, most efficiently the ultraviolet receptor. It was satisfying to have this assumption confirmed. We were nonetheless startled by its implications, because we knew that at any given cross section of the ommatidium the microvillar orientation of the three ultraviolet receptors coincided. This meant that they could provide the analyzing system with only one input channel. Since more than one channel is needed for detecting polarization, more than one ommatidium must be involved. The question was: How many are involved?

At that time Kuno Kirschfeld of the Max Planck Institute for Biological Cybernetics in Tübingen had just proposed a theoretical model according to which three receptors with three different microvillar directions had to cooperate. When my student Esther Geiger and I looked at cross sections over fairly extensive areas of the bee's retina, however, we could not find the three necessary sets of ultraviolet receptors, which should be characterized by different microvillar directions. Furthermore, it had never been proved beyond any doubt that the microvilli of one visual cell were really aligned parallel to one another along the entire length of the cell. The sensitivity of the cell to polarized light should nonetheless depend critically on such an alignment.

As we were working on a three-dimensional reconstruction of the ommatidia in the eye of the bee, a striking feature caught our attention and turned it in a new direction. It turns out that all rhabdoms are twisted. The twist extends the full length of the structure and amounts to about one degree per micrometer. In an elongated cell the twist totals 180 degrees from top to bottom. The twist is either clockwise or counterclockwise. Twists in each direction occur with equal frequency, and ommatidia enclosing rhabdoms twisted each way are randomly distributed in the insect's eye.

Recently Gary D. Bernard of the Yale Medical School and I conducted an optical analysis of the twisted rhabdoms. We discovered that the 180-degree twist deprives the two long ultraviolet-receptive visual cells of any sensitivity to polarized light. The short cell, however, is twisted only some 40 degrees, and so it is not severely deprived of its sensitivity to polarized light. Moreover, half of the short cells are twisted 40 degrees to the right and the other half 40 degrees to the left, so that their directions for maximum sensitivity do not coincide but are at an angle of 35 to 40 degrees. This means that any two short cells of opposite twist are perfectly designed to act as two independent polarization analyzers.

On the basis of these data we have constructed a simple theoretical model explaining how the eye of the insect analyzes the direction of skylight polarization. In brief, the model indicates that if two polarization



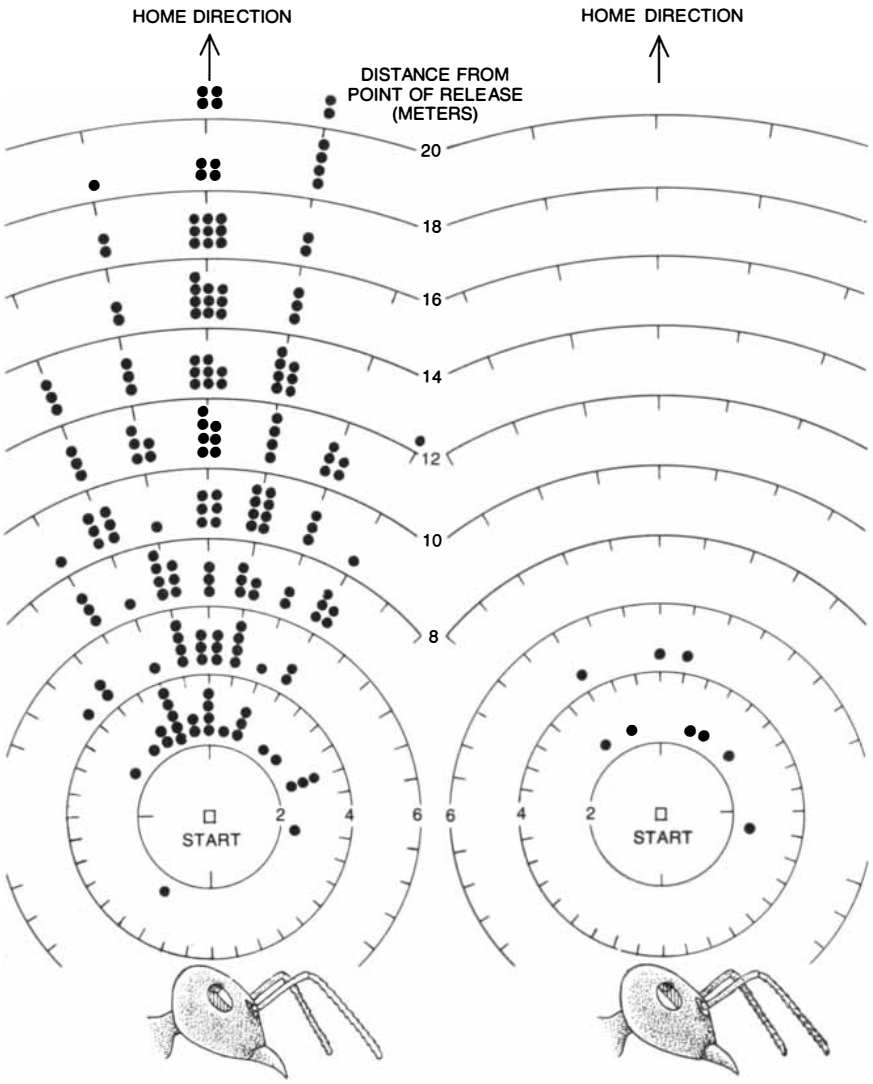

**POLARIZATION-DETECTING SYSTEM of the honeybee is depicted schematically. The ultraviolet receptors of two adjacent ommatidia, one twisting clockwise and the other counterclockwise, are sufficient for the detection of any direction of polarization. Both ommatidia scan nearly the same small patch of the sky, less than five degrees in diameter. In the two ommatidia three types of ultraviolet receptors have to cooperate: polarization-insensitive cells (*signal C*) and two independent polarization-sensitive cells (*signals A and B*). This set of cells can unambiguously detect any direction of polarization (Φ). The directions of maximum sensitivity of the two polarization-sensitive cells differ by about 40 degrees, as is shown by the curves at the right. The nerve fibers extending from the ultraviolet receptors extend through the first of the insect's two visual ganglia (the lamina) to the second (the medulla). The nerve fibers extending from the receptors sensitive to green and blue light rather than to ultraviolet end in lamina.**

analyzers of opposite twist work together with at least one long ultraviolet-sensitive cell that is insensitive to the polarization of skylight, then the orientation of the skylight polarization anywhere overhead can be determined unambiguously. Hence any two adjacent ommatidia of opposite twist are equipped with all three of the necessary cells and will provide the analyzing system with all three of the necessary signals: two independent signals that are modulated by polarized skylight and one signal that is not. The unmodulated signal is identical for all the long ultraviolet receptors of the two ommatidia.

The twist of the rhabdoms was surprising at first. After all, a straight alignment of the microvilli had always been considered a prerequisite for the analysis of polarized light. We have come to realize not only that analysis is possible in spite of the twist but also that the twist is exploited in the analytical process. On the one hand the twist ensures that the one long cell of the three is an input channel free of sensitivity to skylight polarization. On the other it ensures that the axes of the microvilli in the two polarization-sensitive input channels point in two different directions.

A skilled engineer could hardly design a simpler and more elegant system. Menzel and his colleague Margaret Blakers, working at the Technische Hochschule in Darmstadt, have found that the eye of a large hunting ant, the bulldog ant of Australia, has the same two kinds of oppositely twisted rhabdoms. Thus it appears that the eyes of ants as well as those of bees have a set of ultraviolet-receptive visual cells that are specially adapted to the strategy of detecting the polarization of skylight.

To recapitulate, any system that is capable of unambiguously analyzing polarized light with only one type of color receptor has to be fed by three independent receptors. That is because any state of partially polarized light as it is analyzed by an insect can be completely described by three independent numbers: direction of polarization, degree of polarization and mean intensity. If all three receptors are sensitive to polarized light, they have to show maximum sensitivity in different directions. In an insect's eye this would mean that three ultraviolet receptors with different microvillar directions would have to cooperate. In the bee, however, only two of these polarization-sensitive receptors function. Since their directions of maximum sensitivity are neither parallel nor crossed, they have only to cooperate with a polarization-insensitive receptor, a long twisted ultraviolet receptor cell, to get all the information on a given state of polarization. There are several reasons why the system with two polarization-sensitive receptors is more advantageous than the system with three. One reason, to which I shall return, is that the long twisted ultraviolet receptor can also contribute to color vision without introducing a polarization-sensitive signal into that system.




**LOCATION OF OMMATIDIA in the desert ant's eye that perceive polarized ultraviolet radiation was confirmed experimentally by covering parts of ants' eyes with opaque paint. At the bottom are the heads of two experimental ants. The ommatidia that are sensitive to polarized ultraviolet radiation are at the upper front part of the eye (*small spot of color*). When the rear third of the eye was covered with paint (*hatching*), the ants' navigational ability was scarcely affected (*diagram at left*). Ants released at the starting point were found at various distances (*black dots*) along the way home. When the front third of the eye was covered, however, only a few of the ants went beyond the circle two meters from starting point, and none passed six-meter circle (*diagram at right*). Ants that remained within two-meter circle were not recorded.**

The eyes of ants and bees, with their large number of ommatidia, simultaneously scan many different parts of the celestial hemisphere. And as we have seen, the light from the celestial hemisphere is differently polarized at different points in the sky. Neither insect, however, seems to have a nervous system complex enough to process signals from thousands of points in the sky. How many of these ultraviolet receptors are actually used for navigation, and which ones are they? We sought answers to these questions in two different ways. One was to cover specific regions of an ant's eyes with opaque paint and then observe its behavior. The other was to add a device to our tracking vehicle that enabled us to restrict the ant's view of the sky to one part or another of its normal visual field. Both approaches soon demonstrated to our satisfaction that the part of the compound eye utilized by our desert ants for the detection of polarization is a small region near the upper edge of the eye. This specialized area is physically apparent from above the ant's eye as a small depression in the array of ommatidium lenses. Moreover, my former graduate student Paul L. Herrling has examined the structure of the visual cells of the ant and has found a completely different type of rhabdom near the upper edge of the eye.

The ant's dependence on the signals from this specialized area is dramatic. Insects can move their eyes only by moving their heads. When we blacked out the lower part of an ant's visual field (by inserting a screen in the device on our tracking vehicle), its behavior was unaffected until the blackout reached

the lower edge of the area specialized for polarized-light perception. Then each upward shift of the screen was matched by a compensating upward tilt of the ant's head. As the screen was moved upward toward the zenith, a point was reached where the ant could not lift its head any higher; it would then turn a backward somersault, ending the experiment. By motion-picture analysis of the head positions we were able to plot the dimensions of that part of the eye which is concerned with the detection of polarized light.

In mapping the areas of the eye that play a role in skylight navigation we arrived at a further conclusion: In both ants and bees fewer than 10 ommatidia in the upper part of the eye are enough for the detection of polarization. So far our results do not allow us to judge whether the theoretical minimum predicted by our model—two adjacent ommatidia of opposite twist—might suffice or whether several pairs of ommatidia must cooperate to provide the precision necessary for navigation.

Here the last of the three questions arises. If an insect can unambiguously determine the direction of polarization at any point in the sky, does this ability in itself guarantee that the insect can navigate unambiguously? The answer is no. The one would unerringly lead to the other only if every point in the sky had its own exclusive direction of polarization. Such is not the case; any given direction of polarization is found at many different points in the sky.

How does the insect cope with this complicated and potentially ambiguous situation? It is hard to believe that the information about all the directions of polarization varying between different positions in the sky and different times of day are stored in an insect's brain. Most likely the insect applies a general rule. What is that rule?

Let us consider some possibilities. There is one point in the sky the insect can always view regardless of whether it is moving north, south, east or west. That point is the zenith. According to the general rule of skylight polarization outlined above, the solar meridian (the arc through the sun and the zenith) extends at right angles to the direction of polarization in the zenith. Therefore, knowing that direction, the insect knows the position of the solar meridian in the sky. What it needs for an unambiguous decision is merely some means of deciding between both arcs of the solar meridian. Any additional cue that differs between both arcs of the solar meridian could suffice: the degree of polarization, the hue of color or the intensity of ultraviolet radiation in the sky.

Our desert ant, however, does not view the zenith with the region of the eye specialized for skylight navigation, so that a more general possibility has to be considered. If the degree of polarization is sufficiently high, the direction of polarization is parallel to the horizon at every point on the solar meridian. If one proceeds along a circle of given elevation from one arc of the solar meridian to the opposite arc, the direction of polarization first deviates increasingly from the horizontal and then approaches the horizontal again. Does the insect "know" this relation?

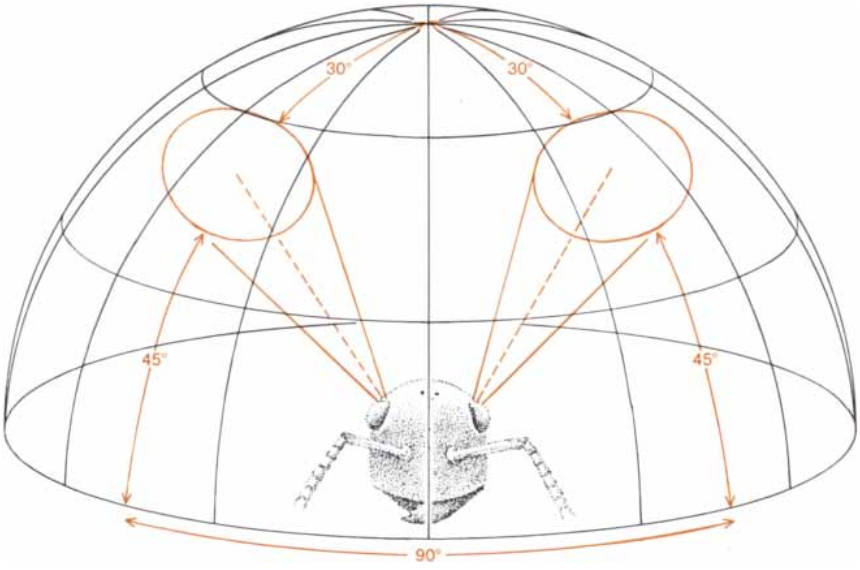
In collaboration with Martin Lindauer of the University of Würzburg and my student Samuel Rossel I have tested the hypothesis, using bees as the experimental animal. From a practical point of view it might appear more difficult to perform the appropriate experiments with bees than it is with our desert ants. This would be true if it were not for a behavioral characteristic of bees: the workers communicate with their fellows, translating the course to be flown to a source of food into the direction of their "waggle dance" inside the hive. The direction of the bee's waggle dance on a horizontal honeycomb coincides with the direction of its foraging flight, provided that the bee can see the sky as it dances. Hence one can confine the bee's vision to certain parts of the sky and observe the effect of this limitation on its capacity to navigate, that is, to dance correctly.

For our experiments we placed a horizontal comb inside a planetarium dome where we could keep the bees from seeing any areas of the outside sky other than the selected ones. The bees had previously been trained to fly in a certain direction and to forage at a distant food source. Each bee was individually marked with a color code. In each test the patch of sky visible to the bee was so small—10 degrees in diameter—that only skylight with a single direction of polarization entered the planetarium.

Under such conditions the bees alternately danced in two directions: in the correct direction and in another direction they had never flown. This is exactly the result one would expect, because in general each direction of polarization is found twice in a circle of given elevation. Since in our experiment the bee was allowed to view only one point in the circle of given elevation, it could not decide between the two different navigational courses indicated by an identical direction of polarization.

Surprisingly, however, the wrong direction as danced by the bee did not coincide with the wrong direction as calculated by the actual distribution of polarization angles in the sky. The mismatch between the expected dance angle and the real dance angle was not accidental but consistent. Even more surprising, we were able to mislead the bees. With the aid of a polarizer we could change the direction of polarization in the point of the sky viewed by the dancing bee. When we changed it to those directions that did not occur in the natural sky at that elevation, the bees nonetheless showed a consistent orientation. What we had expected, of course, was a random orientation. This finding is exciting and may well lead to an overall solution of the insect-navigation problem. We do not yet have all the pieces needed to complete the jigsaw puzzle. All our evidence points, however, to the fact that the bee's brain incorporates a rather generalized and simple representation of the distribution of polarized light in the sky.

Recently Kirschfeld has proposed an elegant means by which the bee could navigate using the direction of polarization in any point of the sky and the elevation of the sun. So far, however, the bee's brain has turned out to be complex enough not to reveal its strategies to the human brain. The fact remains that both bees and ants do navigate successfully. Whereas our experiment demonstrated that ambiguity will disrupt a worker bee's navigation, the disruption

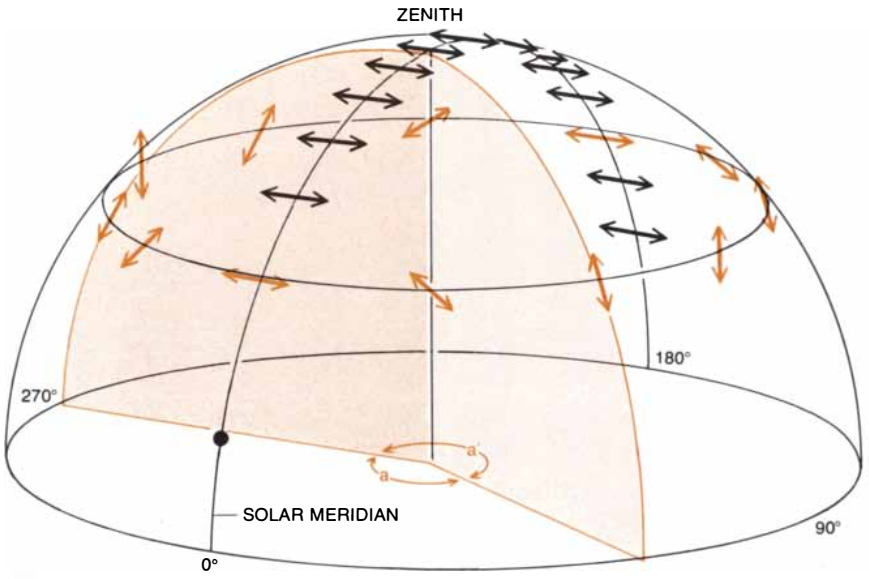



**SPECIALIZED EYE REGIONS, consisting of only a few score of the 2,400 ommatidia in the desert ant's two eyes, scan a region of the sky from 45 to 60 degrees above the horizon when the ant is in a normal running position. Each of the specialized regions points in a different direction horizontally; the angle separating the two points of view is approximately 90 degrees.**

took place only when the bee's access to skylight was confined to light with a single direction of polarization. This is a highly artificial situation a worker bee is unlikely to encounter with any frequency during its short life. As soon as a bee is able to detect polarized light from more than one point in the sky the situation becomes unambiguous. The bee dances in a single direction only: the correct one.

There is one point in the sky that by itself leads to unambiguity in navigation: the position occupied by the sun. This point lacks polarized light. It is also the brightest point in the sky. When we followed our desert ants after adapting the tracking vehicle so that the entire sky was depolarized, the navigational ability of the ants became very erratic. This happened in spite of the fact that the position occupied by the sun still remained the brightest part of the depolarized sky. One might conclude that whatever the ant's internal representation of the sky may be, the sun may be predominantly recognized as the point of least polarization.

In bees that point has become particularly meaningful. Because bees have developed the abstract language of the dance as a means of telling one another about navigation angles, each individual worker bee must be able to make use of a reference point that is common to all its fellow workers. Moreover, such a common reference point must be uniquely recognizable within the overall pattern of sky polarization. Therefore the position of the sun—the point of zero polarization—is the only point bees could select for unambiguous communication. The importance of the sun as a cue in bee navigation may well have resulted from its lack of polarization rather than from its relative brightness.



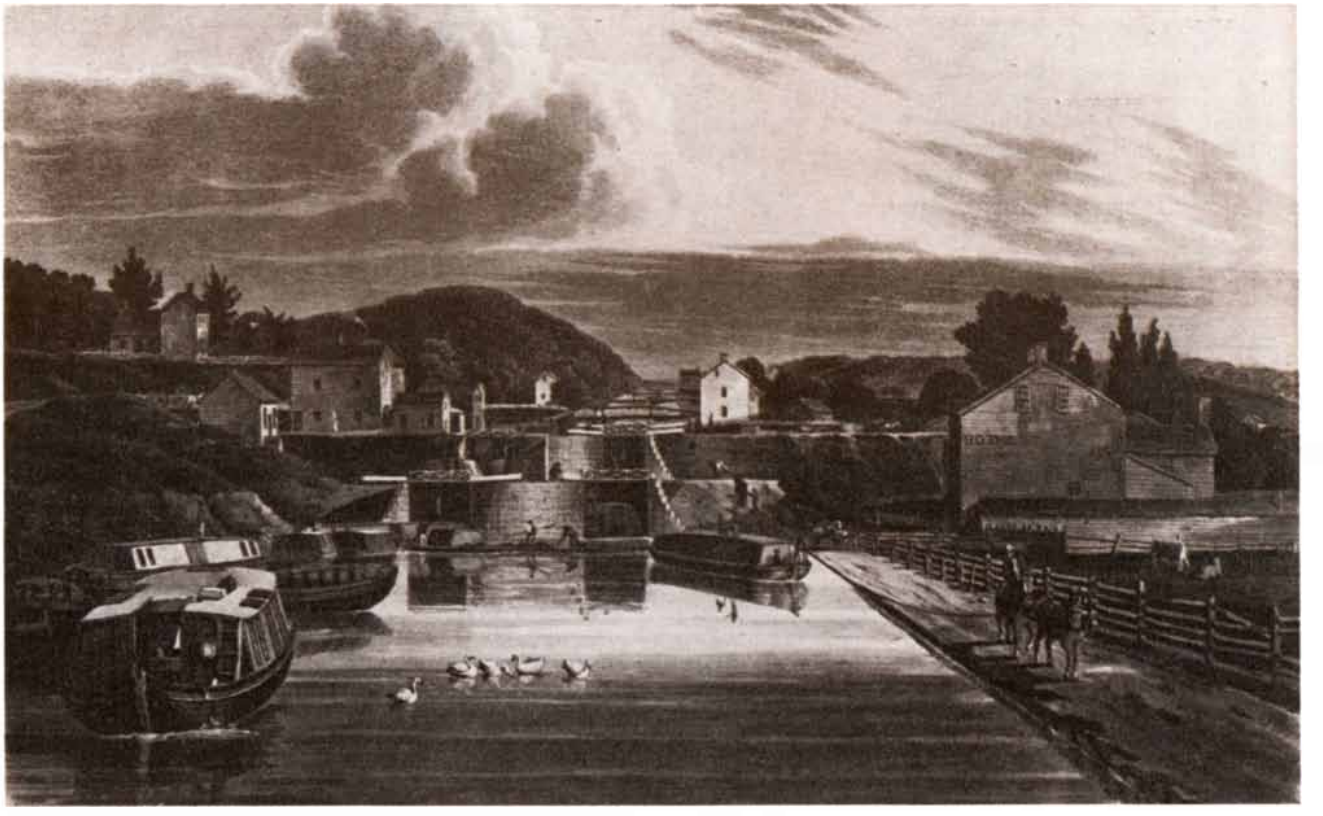

**GENERAL PRINCIPLES OF THE POLARIZATION of the light of the sky are outlined. The arrows indicate the directions of polarization as they would be seen by an observer in the center of the hemisphere. Along the solar meridian (the arc through the sun and the zenith) the direction of polarization is parallel to the horizon. Along most circles of a given elevation the direction of polarization varies through all possible angles. Here the angles are plotted for the circle lying roughly halfway between the horizon and the zenith. In general each direction of polarization is found twice at each circle of elevation. (The angles *a* and *a'* denote the angular difference between the positions of identical polarization.) For this reason there is ambiguity in polarized-light navigational cues unless the insect can view more than one part of the sky.**

What choices, so to speak, had to be made in the evolution of the compound eyes of ants and bees for the ability for celestial orientation to develop? I cannot refrain from speculating on the potentialities and constraints inherent in this process. As an initial assumption, let us accept that the three visual cells of each ommatidium that are ultraviolet receptors evolved specifically to allow a navigational capability based on the polarization of skylight. How about the other six visual cells? In running or flying insects an optomotor, or motion-detecting, system monitors the movement of the environment across the entire visual field and serves to stabilize the animal's course. A number of investigators have demonstrated that in bees these systems that keep the insect on a straight course are almost exclusively triggered by the green receptors. Both in bees and in our desert ants the nerve fibers of the green receptors are relatively short, so that they terminate in the first of the insect's two visual ganglia, the lamina. The three ultraviolet receptors, however, have long nerve fibers; they project through the lamina to the second visual ganglion, the medulla. It seems to me most likely that these two separate subsystems, each of which is incapable of detecting colors alone, are the ones that appeared earliest in the evolution of the insect eye. The ultraviolet system, dealing with celestial cues, has been designed to determine the direction of course in long-range orientation. The green system, on the other hand, became involved in the maintenance of course by exploiting the apparent movement of the floating environmental surround.

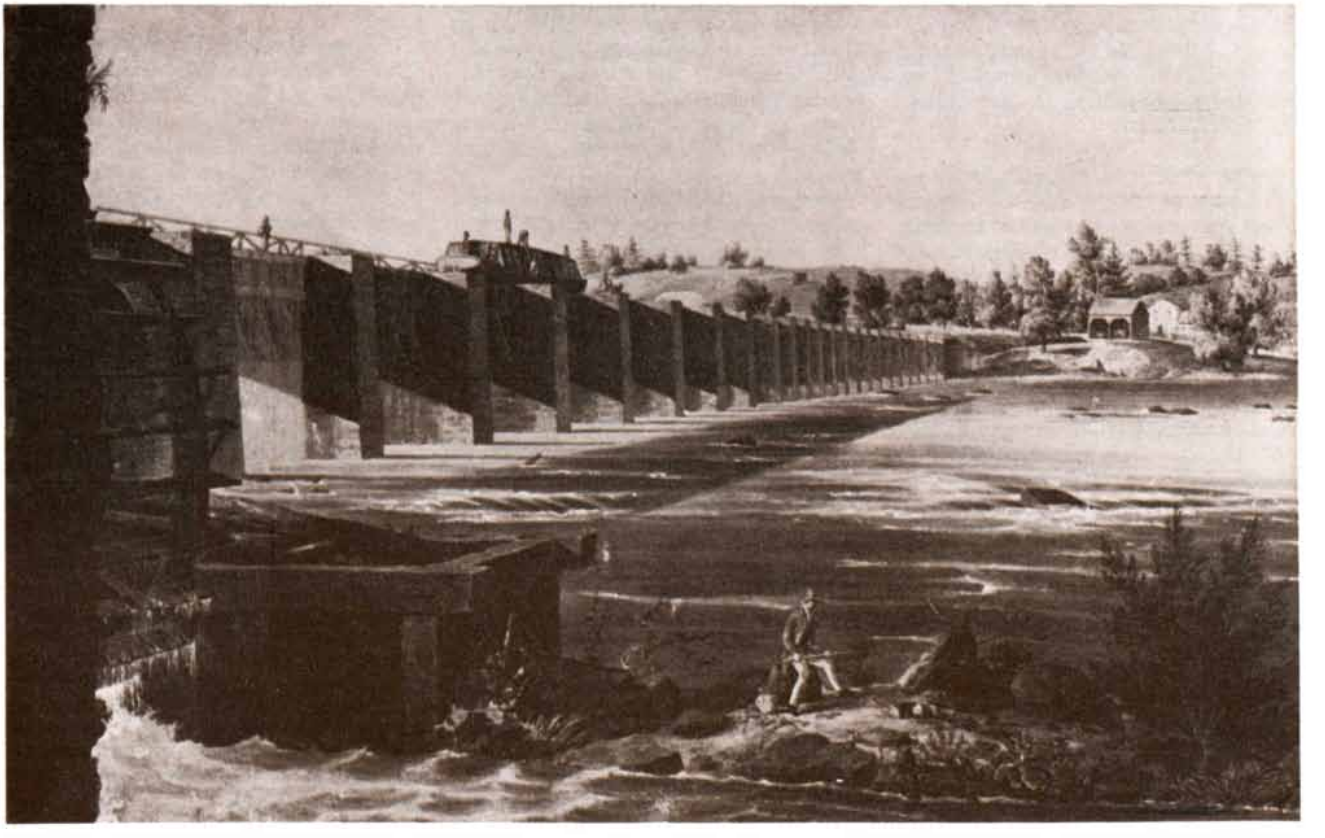
The green system also has to serve another function: the detection of visual objects in short-range orientation. It is likely that mechanisms for object detection have become increasingly important during the insects' evolutionary history. Whereas there is no need for color vision in celestial navigation and optomotor course control, color vision remarkably improves any mechanism that mediates the detection of objects. For bees the selective advantage of such an advance would probably have expressed itself from mid-Cretaceous times, some 100 million years ago, because it was then that the angiosperm plants, with their conspicuously colored flowers, first appeared. We can postulate an interactive evolutionary process that led on the one hand to the diversification of colors in flowers and on the other to the development of color vision in insects. For color vision to be possible, communication between the green and the ultraviolet channel had to be established. Indeed, the lamina of ants and bees is the site of synaptic connections between the two. In addition visual cells sensitive to light at blue wavelengths evolved, making the bee's color perception trichromatic. The two blue receptors are most likely derived from two of the original six green receptors. Like the green receptors, the blue receptors have short nerve fibers that terminate in the lamina.

Different selection pressures have acted on the different visual subsystems. Sensitivity to polarized light, the sine qua non of navigation by skylight, is an entirely undesirable property when terrestrial cues need to be analyzed. That is because the polarization that results when light is reflected from terrestrial objects actually blurs the images of the objects, thereby decreasing visual acuity. As we have seen, the twisting of the rhabdom disposes of this disturbing effect for the long ultraviolet receptors; it does the same for the green and blue receptors, which are equally long. It is hard to imagine how evolution could have solved the problem of using a limited number of receptors for quite different sensory performances more efficiently. Color vision is insensitive to polarized light because the rhabdoms are twisted, and polarization vision is insensitive to the hue of color because it is confined to the ultraviolet receptors.

The insect's principal task in navigation is the retention of consecutive dead-reckoning summaries. For example, during an ant's foraging run its brain has to compute all the angles the animal has turned and all the distances it has traversed and to integrate all these vectors continuously. It is on the basis of such continuous integration that the brain is able to calculate the heading enabling the ant to return to its nest on a straight line from any point on its foraging course.



**ERIE CANAL LOCK SCENE, pictured early in the 1830's by the American artist John Hill, shows a downstream-bound barge under tow after passing through the lock gate (*center*). At left a number of freight and passenger barges are waiting their turn to move upstream.**



**CANAL AQUEDUCTS ON THE ERIE enabled the barges to cross streams encountered along the right-of-way. This painting by Hill shows a passenger barge being towed along the aqueduct over the Mohawk River 15 miles west of canal's junction with the Hudson River.**

# Canals in America

*They did much to open up the interior of the new United States. Although inland waterways still play a major role, the original canal boom quickly came to an end with the rise of the railroads*

by John S. McNown

In the days when the principal prime mover was the horse the most efficient avenues of inland transport were waterways. For many centuries they were navigable streams, and each such avenue was interrupted by non-navigable stretches. In Europe engineers of the 16th century began to extend the waterway network; their endeavors continued on a much larger scale in the next two centuries. At first the work was confined largely to improving the navigability of rivers by removing obstacles or digging canal loops around rapids or other barriers. It gradually became apparent, however, that man-made waterways were superior to natural ones in many respects. The sequence of events in England provides an example.

At the beginning of the 17th century the total length of English navigable waterways was some 650 miles, all of it open river. By 1760 more than a century and a half of river engineering had increased the figure to some 1,200 miles. In the next four decades alone the excavation of barge canals almost doubled the mileage of English waterways. It is little wonder that Benjamin Franklin, witnessing the work in progress in 1772, wrote from London to the mayor of Philadelphia praising the innovation:

"They seldom or ever use a River where it can be avoided," he noted. "Locks in Rivers are subject to many more Accidents than those in still water Canals; and the carrying away [of] a few Locks by Freshets of Ice not only creates a great Expense, but interrupts Business for a long time till repairs are made.... Rivers are ungovernable things, especially in Hilly Countries. Canals are quiet and very manageable. Therefore they are often carried on here by the Sides of Rivers, only on ground above the Reach of Floods."

Franklin might have cited another motive for the innovation: barges maximized the efficiency of the prime mover. In transporting goods with horses the least efficient method is putting the load on the back of the horse; a packhorse can carry only about 250 pounds. A horse drawing a wagon can do much better; even if the road is rough, it can move perhaps 1,200 pounds, and if the road is paved, it can move two tons. A horse pulling a barge does best of all; it can move 50 tons with no more effort than is required to draw a wagon. For Colonial America, with few highways and none of them paved, the attractions of a network of barge canals were obvious.

Canals were not unknown in America at the time Franklin wrote. Like the early canals of Europe, however, they were short bypasses to avoid obstacles on natural waterways. For example, one canal in Virginia detoured the rapids on the James River above Richmond, and another in Massachusetts enabled traffic on the Connecticut River to avoid South Hadley Falls north of Springfield. Had it not been for the Colonies' overriding concerns in the next few decades, first with the fight for independence and then with the problems of emergent nationhood, the era of the barge canal in America might not have been postponed until the 19th century.

What was a barge canal like? Engineering experience had settled the overall geometry of canals well before the end of the 18th century. They were trapezoidal in cross section; at the bottom their width was 20 to 25 feet and at water level it was 30 to 40 feet. The water in them was only three to four feet deep, so that the angle of the sides was quite flat. This gradual slope helped to minimize erosion due to wave action and slumping due to seepage. The barges kept to the midsection of the canal, where the water was deepest, and were hitched by a slack cable to the motive force on the towpath: a horse, a mule, a team of such draft animals or on occasion men. The speed of the tow was from $1\frac{1}{2}$ to two miles per hour.

The loss of water from leakage, particularly in canals dug in porous soil, was minimized by a procedure called puddling. Loam and sand were thoroughly mixed with a little water, and a thick lining of the mixture was applied to the bottom and sides of the ditch. Over a period of a year or two after the canal had been filled with water the lining became progressively tighter until it was virtually waterproof. The converse problem, an excess of water from rainfall, seepage or natural drainage that might fill the canal to overflowing and erode its banks, was guarded against by providing overflow weirs at intervals along the way.

Ideally a canal was built on comparatively flat ground, following one contour line until a change in the terrain forced a change in elevation. Similar changes in elevation confronted the engineer when a canal interconnected with a river, where the difference between flood level and low water can be many feet, or with an estuary, where the daily tides can rise and fall by a similar amount. Such changes in elevation were accommodated by means of locks. A lock is simply a hydraulic elevator that requires no power other than the potential energy represented by a supply of water at higher levels in the canal system.

A chamber in the canal with large gates at either end, a typical lock incorporated a system of valves that allowed the chamber to be filled with water up to the level of the canal above or emptied down to the level of the canal below. When a barge was moving up the canal, the water level in the lock was made equal to the level of the lower canal. The lower gates were then opened, the barge entered the lock chamber and the gates were closed. Next the upstream valves were opened and water from the upper canal filled the chamber until its water level was equal to that of the upper canal. The upper gates were then opened, and the barge continued its progress along the upper canal. In most of the early lock systems the vertical lift was from six to 10 feet.

The paired gates at each end of the lock normally formed a blunt *V* where they met, with the point of the *V* upstream. The configuration has much the same distribution of stresses as a supporting arch. Leonardo da Vinci, who shortly before 1500 proposed such a design for lock gates in the ingenious canal system of Milan, may have invented the *V* configuration. The hydrostatic forces acting in the downstream direction hold the gates tightly together when they are closed, minimizing leakage; the angle of the *V* transfers the load to the strong retaining walls of the lock chamber, providing the necessary support.

In the earliest locks the gates themselves served as the valves that let water into and out of the lock. The hydrostatic forces act-

ing on even small gates, however, are measured in tons, and from the 15th century on the gates were provided with an opening (in many cases more than one) that could be closed with a cover plate. When the cover plate was removed, the flow of water through the gate would fill or empty the lock in a few minutes. Even when the water level was the same inside and outside the lock chamber, considerable effort was required to overcome the friction of the cumbersome gates. The solution was to attach a long balance beam to each gate; the counterbalance offset the weight of the gate and the beam served the lock tender as a lever.

The volume of water required to raise the level in the lock chamber from equal-to-downstream to equal-to-upstream is known as the lock prism; the volume is discharged downstream with each use of the lock. The discharge over a period of time could be halved if every time a barge moved upstream through the lock another barge moved downstream. The engineers compensated for the loss of water due to lock operation and seepage by providing a sufficiently large water reserve upstream.

The need for a dependable water supply at the highest point in a canal system was a factor that set limits on the scope of the system. Where the diversion of local streams would not provide a year-round supply of water it was necessary to build a reservoir and often to cut miles of feeder channel between the reservoir and the canal. At lower points along the system, where the canal more often than not ran parallel to a river, simple diversion sufficed to replace water losses. In a few instances, however, it was necessary to use power to lift the water to the required height. A huge steam engine drove a scoop wheel for this purpose on the Chesapeake and Delaware Canal, where construction began in 1789. It is the largest steam engine still standing on its original foundations in the U.S. today.

The first canals in America, other than short obstacle bypasses, were built to tap natural resources in the interior of the country, to reduce the length of voyages along the coast or to do both. In Massachusetts the Middlesex canal was laid out in 1793, four years after the Chesapeake and Delaware, but it was opened to traffic in 1808, 21 years earlier than the Chesapeake and Delaware. The Middlesex canal linked Boston harbor with the Merrimack River at Lowell, saving a long haul around Cape Ann. The Chesapeake and Delaware shortened the trip between Baltimore and Philadelphia by 300 miles. A third pioneer line, the Delaware and Hudson, carried coal from Pennsylvania to New York City by means of an inland voyage of some 100 miles on the canal and the Hudson River that took the place of a coasting trip of some 550 miles around New Jersey.

Even before the War of 1812 many men of vision recognized the advantages of, indeed the vital need for, connections with the interior of the new nation: between the ports along the Atlantic coast and the Great Lakes and between the same ports and the Ohio and the Mississippi. In the years between the British surrender at Yorktown and George Washington's inauguration as president the general spent months in the Alleghenies surveying routes westward from the upper waters of the Potomac to various branches of the Ohio. In 1808 Albert Gallatin, Secretary of the Treasury under President Jefferson, proposed no fewer than five trans-Appalachian canal systems. In the years after 1812 four of the systems were begun, and two of them were eventually carried through to completion.

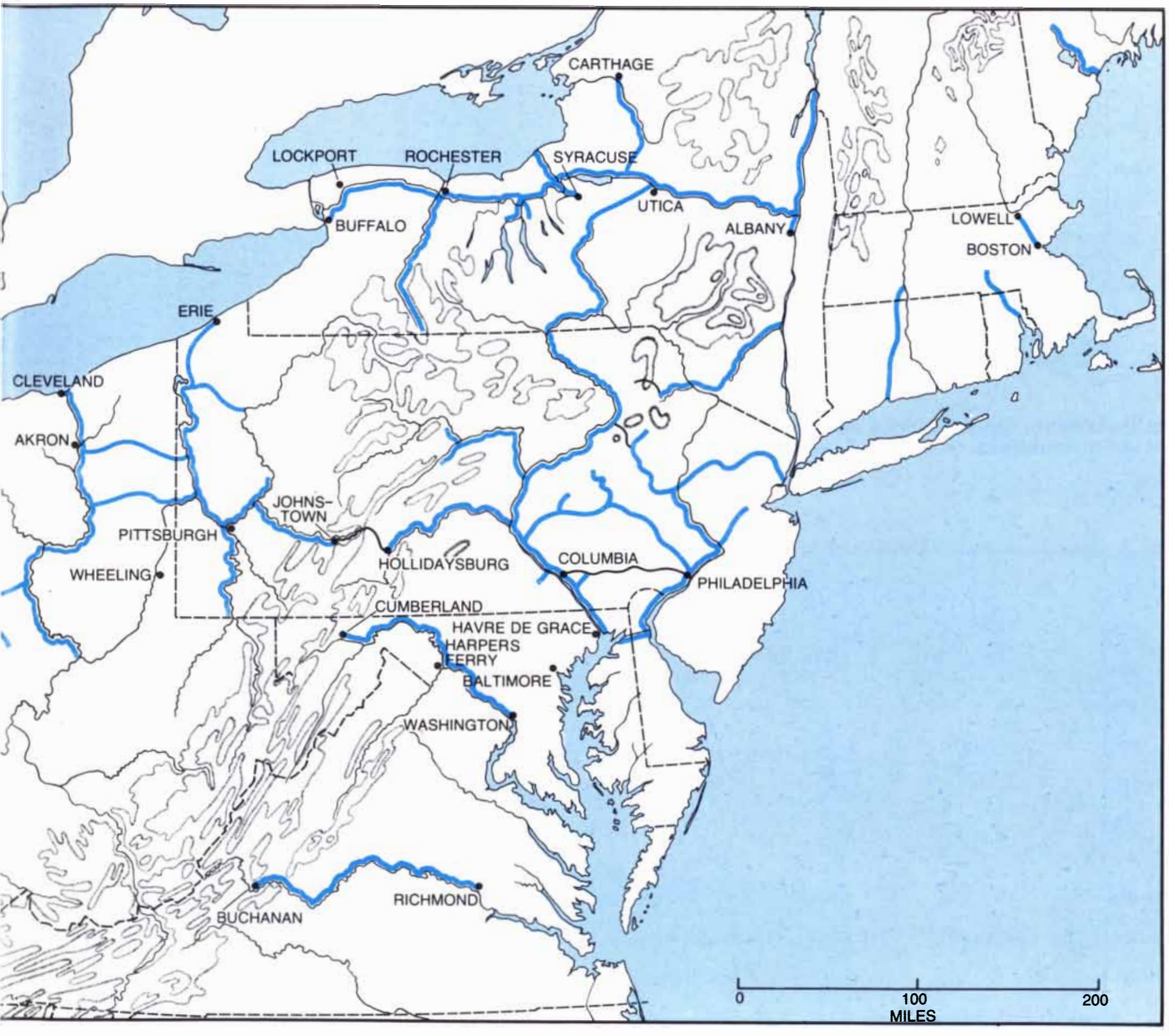
The first and most famous of the four was the Erie Canal. Construction began on one 125-mile-long section of the canal, between Utica and Rochester in New York, in 1818. The route from Albany on the Hudson River to Buffalo measured 350 miles. For much of the way the canal passed through unsettled and virtually unsurveyed wilderness, but the route had a number of advantages. Not the least was the generally favorable terrain: the climb from the Hudson near Albany to Lake Erie was only 568 feet, and most of it, a total of 425 feet, was confined to the first 100 miles, from the Hudson to Utica. From Utica to Rochester the route actually descended before rising, at first gradually and then more steeply, to the Genesee plateau, 504 feet above the Hudson. At Lockport, some 30 miles from Lake


**NETWORK OF CANALS constructed in the U.S., mainly between 1818 and 1860, was designed to attain two principal objectives. The earlier objective was to shorten or eliminate the coastwise movement of freight; an example is delivery of Pennsylvania coal via the Delaware and Hudson Canal and the Hudson River to New York, eliminating a voyage around New Jer-**

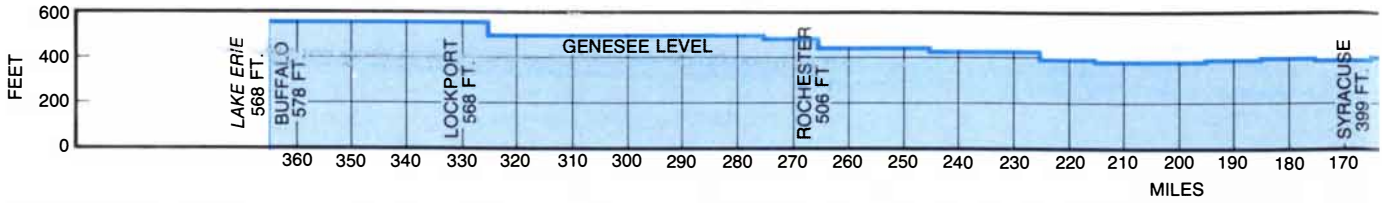
Erie, a steep rise of 60 feet preceded a final level run southwest to Buffalo and the lake. It was not unexpected that the builders of the canal chose to construct its middle section first.

What may well have been unexpected was that construction was begun at all. Before the War of 1812 the canal's proponents in New York had hoped for Federal financial assistance. The war, however, left the Federal Government in debt, and the burden of paying for the canal fell entirely on the state. Opinion on the canal was divided. Many wanted a canal that would be only half as long as the one that was planned. They proposed that it run from Albany to Syracuse and then turn northward along Onondaga Lake to enter Lake Ontario instead of Lake Erie. Others were distracted by regional jealousies. Unable to foresee that the canal would make New York City one of the world's greatest seaports, city politicians were opposed to the entire project. If southern New Yorkers could see no gain in the scheme, eastern New Yorkers were certain that only western New Yorkers would benefit. Supporters of the canal had won state authorization to float a $5 million loan for construction, but in 1814 opponents of the project persuaded the legislature to rescind the authorization.

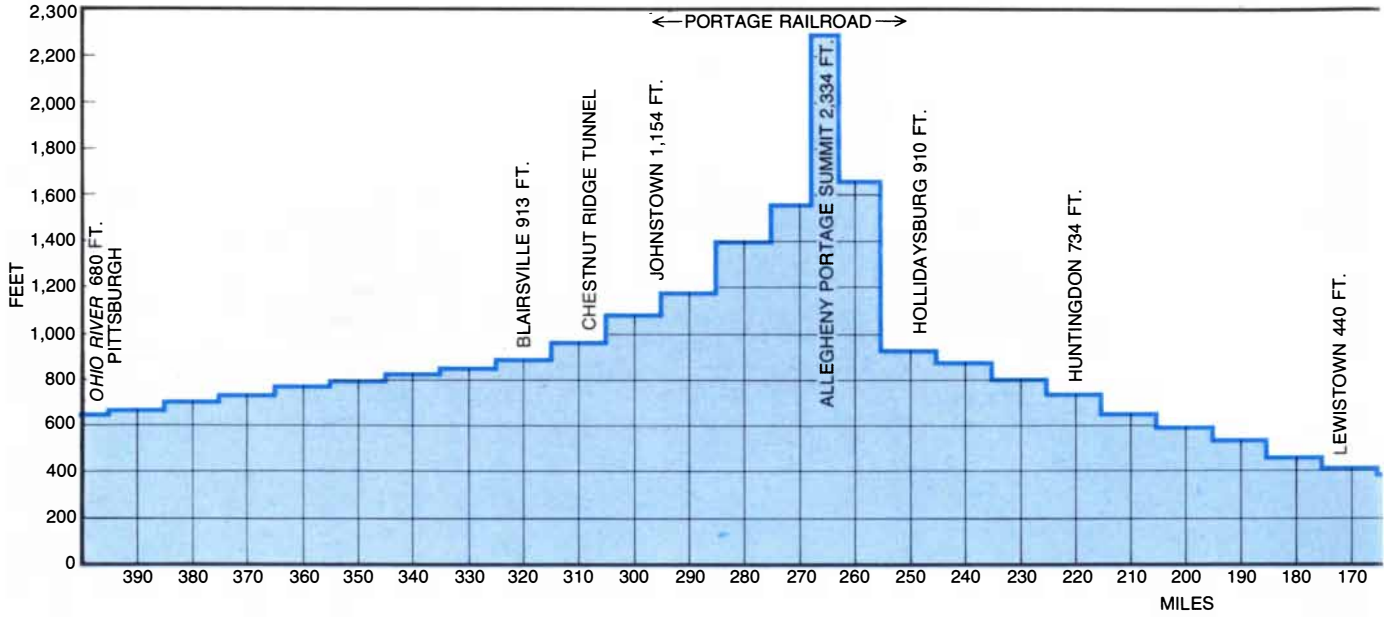
Late in 1815 De Witt Clinton, who not only was state canal commissioner but also was serving his 10th term as mayor of New York, rallied public support for the canal by circulating a committee study in favor of the project. The report took the form of a memorial to the legislature and was discussed in town meetings across the state. It opposed the Lake Ontario route on the sensible grounds that it opened the way to only one of the five Great Lakes. (Niagara Falls blocked the entry to the other four.) More slyly, it pointed out the benefit the Ontario canal would bring to the Canadian cities on the St. Lawrence. The memorial castigated delay and appealed to the people's pride. "It remains for a free state," the committee wrote, "to create a new era in history, and to erect a work, more stupendous, more magnificent and more beneficial



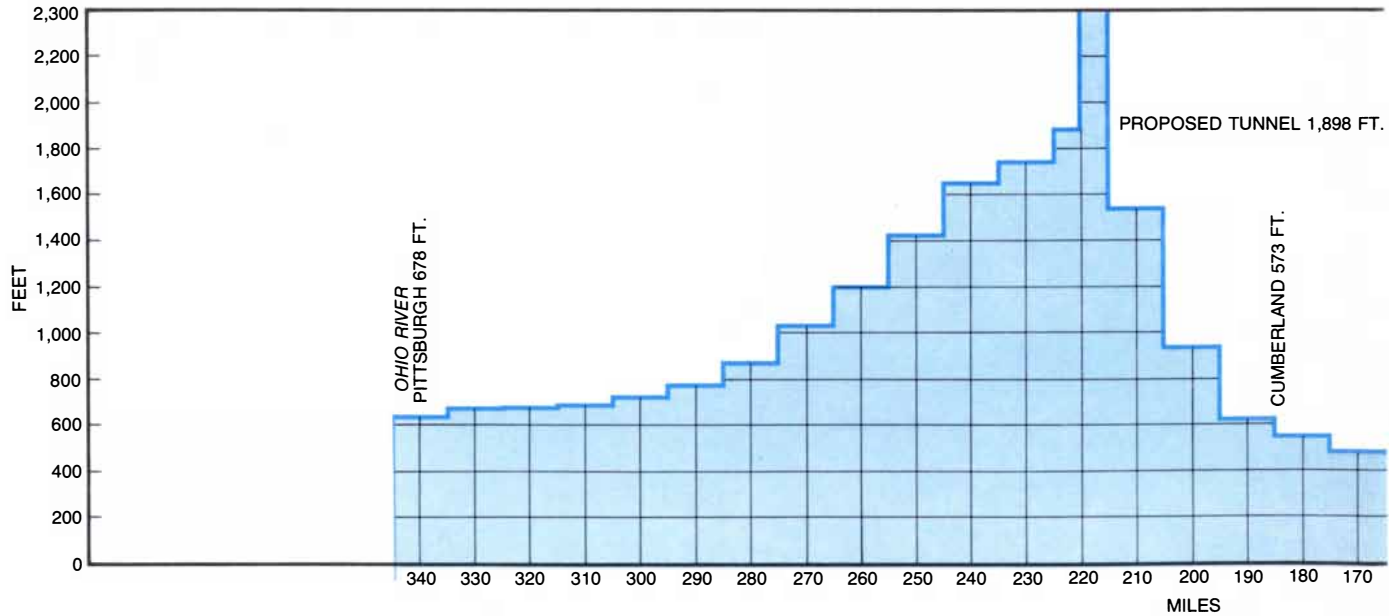

**sey. The later and more important objective was to link Atlantic ports to the Great Lakes and to tributaries of the Mississippi. Three major systems attempted this: first the Erie Canal across New York, completed in 1825; next a combined rail and canal link between Philadelphia and Pittsburgh, completed in 1834, and last a waterway between Baltimore (via Chesapeake Bay and Potomac River) and Ohio River. The canal did not reach Cumberland, Md., until 1848; it went no farther. Rail segments of Philadelphia-Pittsburgh system are in black.**



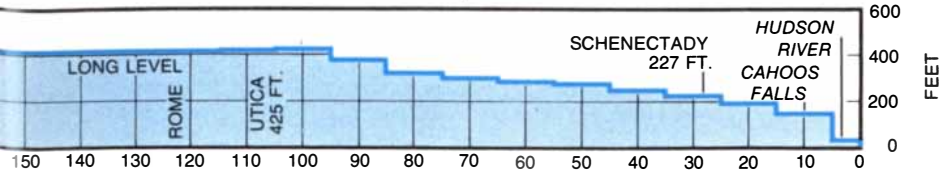

**PROFILE OF THE ERIE CANAL shows a lift of 568 feet over a distance of 350 miles between the Hudson River (*right*) and Lake Erie at Buffalo (*left*). Most of the lift, 425 feet, lay in the 100 miles between the Hudson and Utica, where the major step, 78 feet through**



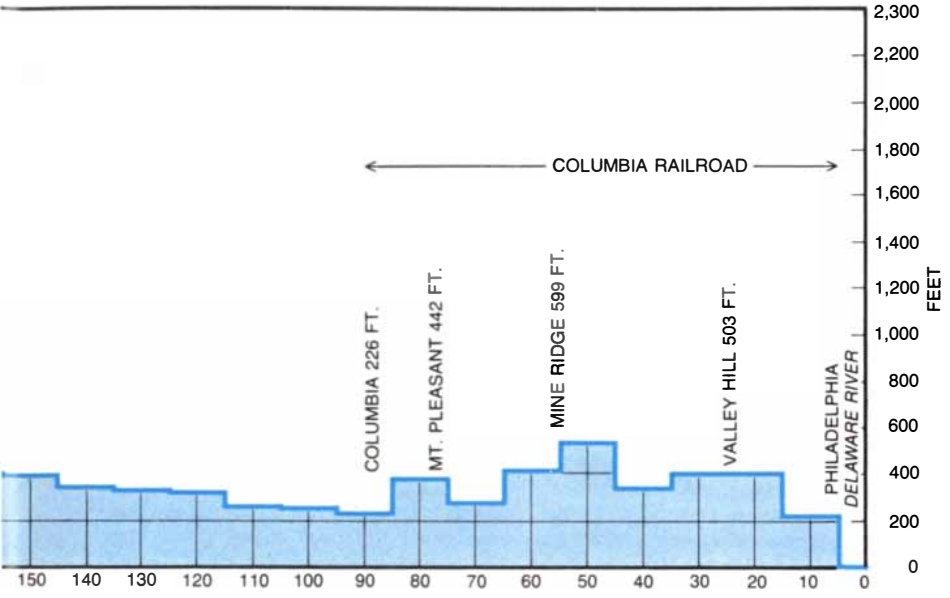

**PENNSYLVANIA CANAL PROFILE shows a 2,334-foot lift from sea level at Philadelphia to the summit of the inclined-rail system connecting Hollidaysburg and Johnstown. The distance from Philadelphia to Pittsburgh was 400 miles; the first 90 miles of the system,**



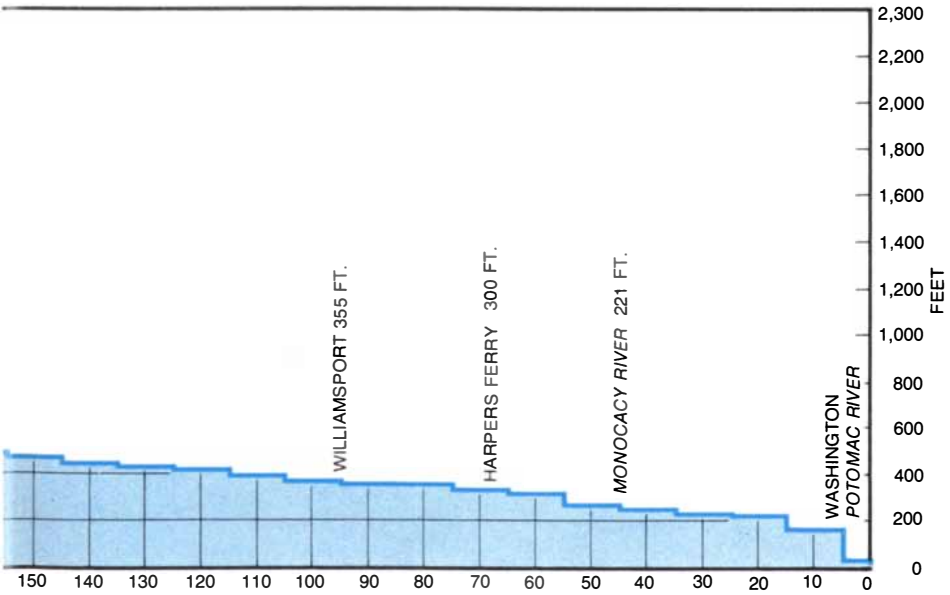

**CHESAPEAKE AND OHIO PROFILE, as proposed, shows a lift from water level at Washington to 1,898 feet, where a four-mile tunnel was to be bored through the Allegheny Mountains some 215 miles west of Georgetown. Ground for the canal and for the Baltimore and**




**nine locks, was at Cahoos Falls. Two other major steps were at Rochester (five locks, 37 feet) and at Lockport (five double locks, 62 feet). Pleasure boats still use parts of the Erie Canal.**




**from Philadelphia to Columbia, was also traversed by rail. The Eastern and Juniata divisions of the canal covered the next 160 miles; the 100-mile Western division reached the Ohio River.**




**Ohio Railroad was broken on the same day: July 4, 1828. The railroad reached Cumberland, Md., in 1840 and the Ohio River in West Virginia in 1857. Only 186 miles of canal were built.**

than has hitherto been achieved by the human race."

The memorial won the support of 100,000 citizens of New York, and early in 1816 the legislature passed an "Act for improving the Internal Navigation of the State" and granted $20,000 to the canal commission for a survey of the route. The cost of construction was estimated at between $5 and $6 million. It was proposed to collect the sum by hypothecating future tolls and by levying a series of nuisance taxes: a tax on salt, a tax on lotteries and auction sales and a $1 charge against all who traveled more than 100 miles by Hudson River packet boat. By 1818, 2,000 laborers and 1,000 horses, mules and oxen began the work.

The work was divided among gangs recruited by individual contractors. Their first task was to clear a right-of-way 60 feet wide along the surveyed route, often through forests so dense that the workers had trouble seeing the line of surveyor's stakes ahead. Once the right-of-way was cleared excavation was begun; the ditch was four feet deep, 28 feet wide at the bottom and 40 feet wide overall. The excavated material was utilized as needed to form ramps on each side of the canal; the ramp that was on the side of the towpath was the wider of the two.

The contractors improvised as they went along. Their ingenuity gave rise to a series of innovations: a horse-drawn scraper, a dumping wheelbarrow, a plow with a deep blade for cutting tree roots and a new kind of stump-puller. Where the right-of-way met streams the canal was carried across by a bridgelike aqueduct; where the ground was too swampy for summer construction work the contractors dug out the frozen muck during the winter.

By October, 1818, a section 58 miles long between Utica and Rome had been completed, and a celebration was held to mark its filling with water. The first vessel to enter the canal was the *Chief Engineer of Rome;* it carried Clinton, who was now governor of the state, and the other canal commissioners on a maiden voyage, powered by one horse, from Rome to Utica. By the end of the year 95 miles of the canal had been finished, and by 1822 the middle section, 220 miles long, was carrying both freight and passengers in some 1,800 barges. The passenger barges emphasized speed: as much as five miles per hour. This pace, however, interfered with freight-barge operation and created waves that damaged the banks of the canal. Accordingly the canal commissioners imposed a speed limit. Unless an operator had received written permission he was not supposed to exceed four miles per hour.

The difficult construction work at both ends of the canal still remained to be done, and many were gloomy over the prospects for its completion. By 1821 Clinton was no longer governor, and his influence was temporarily in eclipse. The project nonetheless

continued on schedule or ahead of it. The canal was finished in October, 1825, a little more than seven years after construction had begun. That year Clinton was reelected governor, and so he was able to preside over the festivities that marked the completion of the work. The total cost had been $8 million, an overrun of some 40 percent, but the canal was still a bargain.

A flotilla left Buffalo for New York City; Clinton, aboard the *Seneca Chief,* led the way during a nine-day voyage that was punctuated with banquets, oratory and fireworks at every night's anchorage. On the morning of November 4 the fleet reached the Battery, at the foot of Manhattan, to be greeted by the citizens of the city, their number increased by some 30,000 visitors who had come to witness the event. A keg of Lake Erie water, carried by the celebrants, was ceremoniously poured into the harbor, as were bottles of water from the Ganges, the Nile, the Orinoco and other rivers.

The Erie Canal was a great commercial success. Traffic was so heavy that soon after the opening celebrations there was serious discussion of enlarging and extending the system. Philadelphia and Baltimore felt threatened by the sudden ascendancy of New York as the principal port for the hinterland; Virginians had visions of an empire across the Alleghenies. Indeed, if the Erie had been less successful, the canal promoters of Pennsylvania and Maryland might have thought twice about challenging the obstacles that lay between their coastal ports and access down the Ohio River to the Mississippi and the West. In particular they might have noticed the first stirrings of competition. By 1829 promoters of surface transportation had built 16 miles of railroad in Pennsylvania, and by 1830 they had built 13 miles in Maryland. The rail cars were drawn, however, not by locomotives but by horses.

In both states major canal construction began within three years after the opening of the Erie. The Pennsylvania plan called for linking Philadelphia with Pittsburgh; work on the Main Line canal began simultaneously at both ends (at Columbia in the east and between Pittsburgh and Freeport in the west) with not much thought about how the junction was to be effected. Unlike the Erie's modest climb of less than 600 feet, the Main Line engineers faced a 2,334-foot ascent to a pass across the Alleghenies.

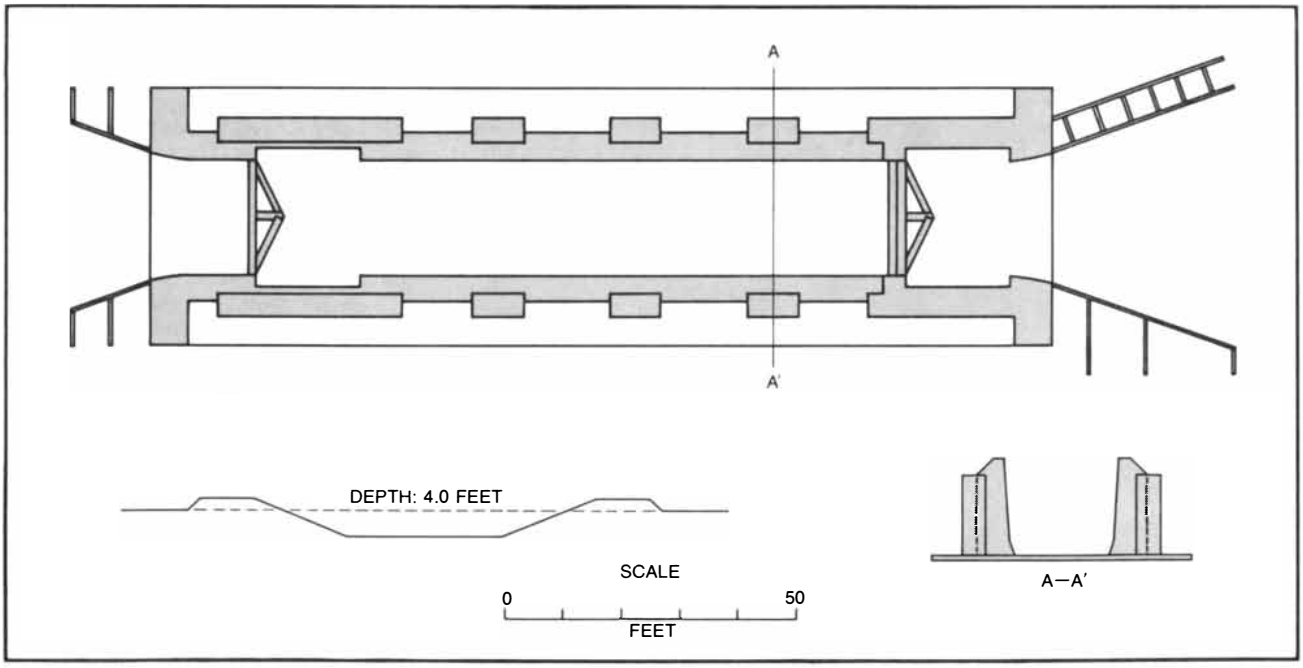
Other obstacles along the Main Line canal were met in stride. The canal was carried across the Susquehanna River behind a 2,000-foot dam; a specially built bridge just above the dam served as the towpath. The Juniata River in the eastern Alleghenies was crossed by a 600-foot aqueduct; on the western side of the mountains access to the Monongahela River was provided by an 810-foot tunnel. It was in the 40 miles of high country between Hollidaysburg and Johnstown, however, that the builders' ingenuity met its severest challenge.

At first it was proposed to avoid the worst of the terrain, including the pass across the Alleghenies, by digging a 4½-mile tunnel. The scheme was vetoed because up to that time no tunnel more than half a mile long had been constructed in the U.S. Finally it was decided to go overland with the new system of surface transport: the railroad. Amazingly the system was completed, rail section and all, by 1834.

The climb to the pass from the canal terminus on the eastern slope of the mountain was 1,400 feet. Much of the 37-mile right-of-way of the Allegheny Portage Railroad was on a reasonable grade, but for thousands of feet the rate of ascent was one vertical foot per 10 horizontal feet. The loaded rail carriages were linked by cable to counterweights at each of the steep inclines, and stationary steam engines powered the winches that dragged the carriages up to the next level. After the pass had been crossed the trip down the western slope involved a descent of 1,150 feet to the head of the canal at Johnstown, on the Conemaugh River. The down trips of the rail carriages in both directions were powered by gravity.

Although freight was loaded from the barges to the rail carriages and back again, passengers on the Main Line canal could remain in sectional canal boats that were taken apart and lashed to the rail carriages. In this way the passengers could travel from Philadelphia to Pittsburgh without changing their accommodations. Charles Dickens made the trip; he was not pleased with his view of "the extreme verge of a giddy precipice... without stone or a scrap of fence between [the car and] the mountain depths below."

By 1854 the Pennsylvania Railroad had also built a line across the Alleghenies. A few years later the railroad bought the Main Line canal and soon closed the western portion and the Portage Railroad. The eastern half of the canal remained in active service; an extension was even built northward




**LOCK ON THE ERIE CANAL (*top*) and profile of the canal bed (*bottom*) are shown to the same scale in these simplified drawings based on contemporary plans. The *V* formed by the paired gates at each end of the lock points upstream; water pressure keeps the gates tightly closed until water levels are equal on both sides. Although locks were built only wide enough for one barge, the width of the canal was more than enough to enable barges to pass each other. The embankments and the towpath were built with earth from canal bed.**

through the Susquehanna valley, linking the Main Line and Erie canals. The truncated system continued as a freight route until the turn of the century.

On July 4, 1828, two groundbreaking ceremonies were held near the nation's capital. One of them inaugurated the Chesapeake and Ohio Canal, a waterway whose promoters intended to link the Potomac River (and thus Washington and Baltimore) with the Ohio River in the vicinity of Pittsburgh. The other ceremony marked the start of the Baltimore and Ohio Railroad's push westward toward the Ohio River at points farther downstream. George Washington, as a strong supporter of a Potomac waterway to the West, may be said to have been the spiritual father of the Chesapeake and Ohio Canal. Charles Carroll, one of the few signers of the Declaration of Independence still alive in 1828, turned the first spadeful of earth on behalf of the Baltimore and Ohio Railroad. It was Carroll who had backed the winner.

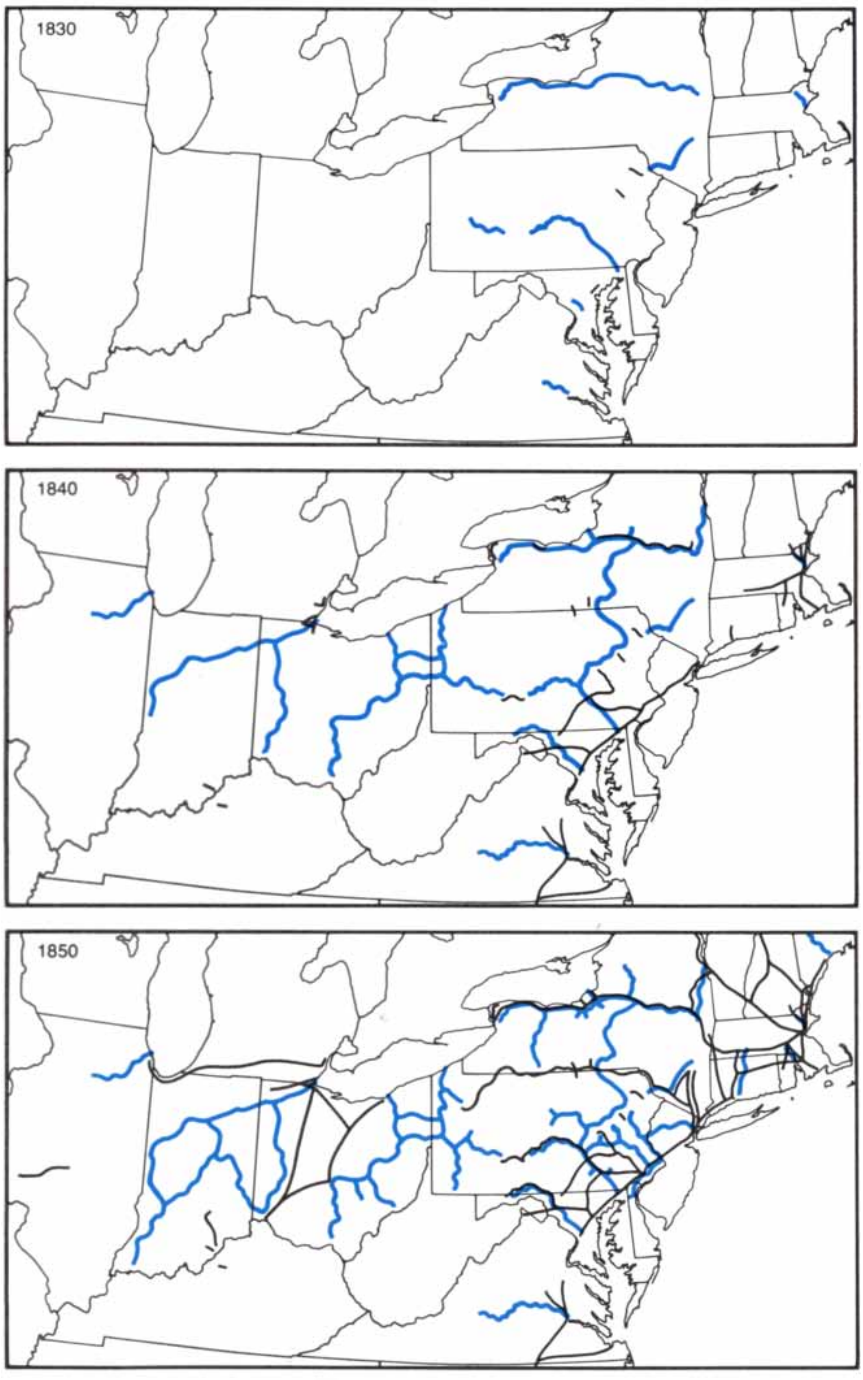
The plan for the Chesapeake and Ohio Canal called for it to be constructed in three sections. The easternmost section was to run parallel to the Potomac by way of Great Falls, Point of Rocks, Harpers Ferry and Williamsport to Cumberland, Md., a distance of 186 miles. This section was substantially shorter than the Erie Canal overall, but its climb—578 feet—was about as great. Although the really challenging terrain only began west of Cumberland, bottlenecks developed at Point of Rocks and Harpers Ferry.

The proposed railroad right-of-way ran more or less due west from Baltimore through Frederick, Md.; it would reach Harpers Ferry on the north, or Maryland, bank of the Potomac. If the canal builders could surmount the physical obstacles at Point of Rocks, the canal would reach Harpers Ferry on the same side of the Potomac as the railroad, and there was scarcely room for both to pass. Before the end of 1828 the two corporations were in court over the question of which had priority. The outcome was favorable to the canal if, but only if, construction proceeded on an agreed-on schedule over the decade ahead.

By 1834 the construction of the canal had passed Point of Rocks and Harpers Ferry and had moved on beyond Williamsport, covering 107 of the 186 miles to Cumberland. The canal corporation, however, had run out of money. If the required schedule was to be met, the 79 remaining miles had to be completed within four years. The state of Maryland grudgingly came to the aid of the corporation with a loan of $3 million. At the same time, however, Maryland lent the Baltimore and Ohio an equal sum and approved a route for the railroad parallel to that of the canal at Harpers Ferry. The railroad builders reached Cumberland within six years; to do the same took the canal builders 14 years. Moreover, by 1857 the railroad had reached the Ohio River at Wheeling and Parkersburg in West Virgin-

ia. The canal never progressed west of Cumberland.

The canal's difficulties were largely financial, but they were not exclusively so. One handicap was that in order to qualify for government support the corporation was obliged to accept government specifications. This meant that the canal had to be built 60 feet wide and six feet deep, dimensions substantially in excess of those that were then customary for barge canals. The requirement greatly increased the cost of various rock cuts, as at Point of Rocks, and particularly the cost of a 3,800-foot tunnel in the section between Hancock and Cumberland. A more serious problem, not only for the Chesapeake and Ohio but also for all other barge canals, was the steady growth of rail transportation that followed the development of a practical steam locomotive. It was Peter Cooper who built such a machine in 1830 at his ironworks in Baltimore; the locomotive was the famous *Tom Thumb,* and the first railroad to benefit from the new prime mover was the Baltimore and Ohio.



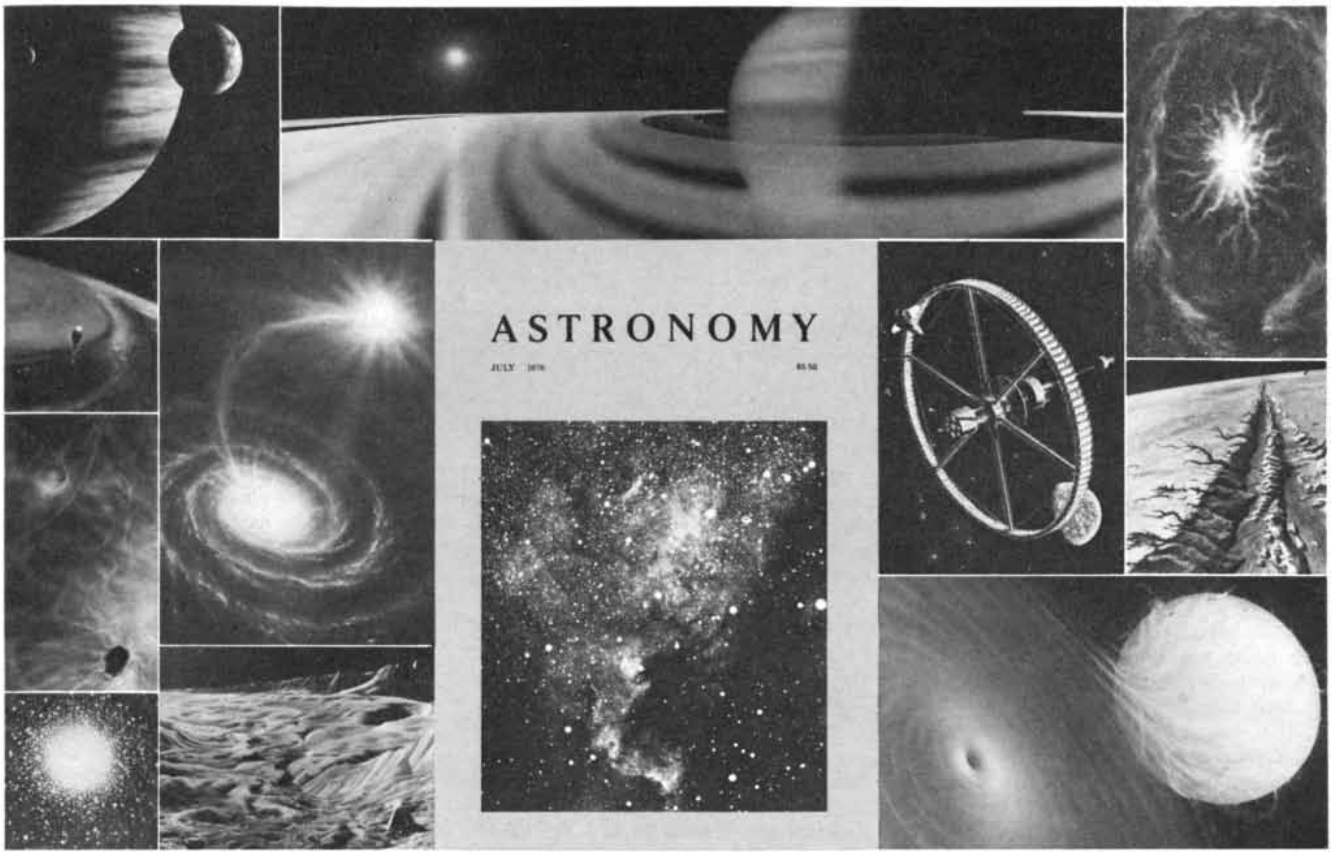

**GROWTH OF RAILROADS in the U.S. north of the Carolinas is shown in successive steps. In 1830, five years after the Erie Canal was completed, only 32 miles of railroad had been built: 16 miles in Pennsylvania, part of it linking Carbondale with the Delaware and Hudson Canal, 13 miles in Maryland and three miles in Massachusetts (*top*). The canals in the same three states had a combined length of 314 miles and the total length of the canals in the states shown was some 1,200 miles. By 1840 (*middle*) the total canal length had risen to 3,181 miles and the total rail length to 2,580. By 1850 (*bottom*) the canals covered some 3,600 miles but the railroads covered more than 9,000 miles. Many of the rail routes were directly competitive with canals.**

Simple growth statistics tell the rest of the story. In 1831 there were fewer than 100 miles of railroad in the U.S.; by 1840 the mileage was more than 3,000, compared with 3,300 miles of canals. By 1850 there were more than 9,000 miles of railroad, compared with 3,600 miles of canals. Of the rail total some 1,300 miles were in New York and 1,200 in Pennsylvania. Maryland had 250 miles of track and Virginia nearly 400. The nation was to see another half century or so of barge-canal operation and some additional construction, but the barge cargoes would include decreasing amounts of perishable goods and the passenger barges were destined to vanish.

Even at 15 miles per hour, about the top speed of the first locomotives, passengers and goods moved at three to five times the speed of the barges. By the turn of the century a quarter of a million miles of railroad track had been laid and some of the busiest canals of the 1850's had silted up and been forgotten. Meanwhile the fourth of Secretary Gallatin's five proposed trans-Appalachian canal systems, the James and Kanawha Canal in Virginia, had failed to progress westward of Buchanan, 196 miles upstream from Richmond. Ground was never broken for Gallatin's fifth system.

Today the U.S. has a network of inland waterways that carries roughly a sixth of all the nation's freight in multiple-barge "tows" that are usually pushed, rather than pulled, by powerful tugs. A system of locks and dams on navigable rivers has almost completely supplanted the entirely man-made waterway. From the engineering point of view this represents a return to the inland-waterway systems of the days before the barge canals, although the systems are on a far larger scale. Dredged river channels, dams and the controlled release of impounded water have removed the extreme seasonal variations in depth of water that plagued the rivermen of the 17th and 18th centuries. Rivers may still go on a rampage, as Franklin noted, but most of the time they are tamed by reservoirs and dams. Today's canals are once more short detours; there are 27 such lock-and-canal loops on the Mississippi (all between Cairo, Ill., and Minneapolis) and 50 on the Ohio. Thus the barge-canal era in America has ended. Ironically the automobile and the airplane have now done to passenger travel by rail what the railroads did to the passenger barge. Nevertheless, thanks to continued river engineering and the development of prime movers with the power of thousands of horses, the inland waterway remains among man's most efficient avenues of transport.

# Man's Dream of Worlds Unseen

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# MATHEMATICAL GAMES

## *Fun and serious business with the small electronic calculator*

by Martin Gardner

If you could climb into a time machine and go back to ancient Athens for a visit with Aristotle, what could you carry in your pocket that would most astonish him? I suggest it would be a pocket calculator. Its Arabic number system, its light-emitting diodes, its miniaturized circuitry isomorphic with Boolean logic (Aristotle, remember, invented formal logic) and above all its computational speed and power would intrigue him more than any other small object I can think of.

The revolutionary consequences of these miraculous little gadgets are only beginning to be manifest. Among engineers and scientists the slide rule has already become almost as obsolete as the abacus. It is sad to think of the mathematicians of recent centuries who devoted years to the arduous calculation of logarithms and trigonometric functions. Today an engineer finds it takes less time to calculate such numbers all over again on a pocket machine than to look them up in a book or make a slide-rule approximation.

Among mathematics teachers controversy over the "new math" has been replaced by controversy over how pocket calculators should be used in elementary education. Almost everyone agrees that at the high school level and above the machine will be an enormous boon. "It is unworthy of excellent men," wrote Leibniz (who invented a mechanical computer), "to lose hours like slaves in the labor of calculation." Freed from such drudgery, students surely will be more inclined to study the basic concepts and structures of mathematics. It is no credit to our education that when a mathematician discloses his profession to a stranger, he waits for the inevitable remark: "I can't even balance my checkbook." Would you tell a poet or a novelist about your spelling difficulties?

Teachers are arguing not about the ultimate value of the pocket calculator but about when it should be introduced. The consensus is that it should not be until a child has learned how to add, subtract, multiply and divide on paper. After that there seems to be no good reason for not allowing students to take a calculator to class or even to use one in examinations. In any case the revolution is unstoppable. Already there is talk of having calculators built into desks like old-fashioned inkwells.

The recreational-math buff who buys even one of the least expensive calculators will soon be wondering how he ever managed without it. Consider a cryptarithm such as

```
  THIS
    IS
 **TOO
HARD*
******
```

Few tasks could be more boring than solving this puzzle without a calculator. It is apparent that $S$ must be 2, 3, 4, 7, 8 or 9 (otherwise $S$ and $O$ would not be distinct), and $I$ cannot be 0, 1 or the same as $S$. One can easily determine by hand that $IS$ must be 72, 57, 68 or 79. From here on, however, there are no good clues, and one needs a calculator to run through the possible values of $T$ and $H$ in a reasonable time. (We assume the usual conventions: each letter stands for only one digit, different letters stand for different digits, asterisks represent any digit and numbers do not begin with 0.)

There are so many other ways that pocket calculators stimulate interest in both serious and recreational mathematics that I can touch on only a few high spots. If the machine has a memory key that makes it possible to hold the partial sums of a converging infinite series, it can be of enormous value in guessing the limit before searching for a proof. For example, take this unfamiliar series in which the numerators are the odd numbers in sequence and the denominators form the doubling series:

$$1/1 + 3/2 + 5/4 + 7/8 + 9/16 + \ldots.$$

After each division add the result to the previous sum. The partial sum, after 10 fractions have been added, is 5.95.... The series seems to be converging on 6. Is that the limit?

Try entering any number in the readout and then repeatedly pushing the square-root key. You will see the roots quickly converge on 1. Suppose that after each square-root extraction you double the result before taking the next root. Is the limit 2? No, it is 4. Instead of doubling, each time multiply by $m$. The limit proves to be $m^2$. Generalize further by taking repeated $n$th roots (if your machine can do it) and multiplying each result by $m$. Can you write and prove the formula for the limit? (I am indebted to Don Morran for this problem.)

Several books have been written on competitive games between two or more players that make use of pocket calculators, but few of the games use the machine for more than rapid calculation. Lynn D. Yarbrough's "keyboard game" is a pleasant exception. It appeared in the special games and puzzles issue (January, 1976) of the stimulating new magazine *Creative Computing,* which is devoted to recreational and educational aspects of computer science. (The magazine is published bimonthly by Ideametrics, P.O. Box 789-M, Morristown, N.J. 07960, and for individual subscribers costs $8 per year.)

The keyboard game begins with the first player entering any positive integer, say 100. The second player punches the subtract key, then any digit key on the three-by-three array [*see illustrations on opposite page*] and finally the equals key. The game continues with players alternately subtracting digits (0 excluded) until a player loses by activating the minus sign.

There is one condition that prevents this game from being trivial. On each turn, after the first subtraction, a player must choose a key adjacent (orthogonally or diagonally) to the key last pressed. Thus if 5 is played, the next player may subtract any digit except 5. If 4 is played, the next play is limited to 1, 2, 5, 7 and 8. If 3 is played, it is limited to 2, 5, 6 and so on.

Without this proviso the first player can win easily by choosing a multiple of 10 for the initial number and then subtracting the right-hand digit of the readout whenever it is his turn. With the proviso the game is fun to play. Better still, it has a surprising solution. It turns out that the second player (the one who makes the first subtraction) can always win regardless of the initial number. If the beginning number is greater than 15, he wins by punching either 1 or 3 (it makes no difference which) until the total is 13 or less and then playing carefully thereafter. Interested readers can consult Yarbrough's article for the complete strategy and for variants of the game when 0 is allowed.

One of the more curious recreational uses for the pocket calculator is as a device for performing magic tricks, most of them of the ESP variety. Here is a stunt that children find particularly amusing. Ask a child to enter 98765432 and divide by 8. He will be mildly surprised by the result: 12345679. The digits are in sequence except for 8, the divisor, which has mysteriously vanished.

Ask the child to name his favorite digit. Suppose he says 4. You immediately say: "Very good. Multiply the number on display [12345679] by 36." Now he is really surprised, because the number he gets is 44444444 (or nine 4's if the readout can accommodate that many). The multiplier you give is always the product of 9 and the

named digit. The working is easy to understand: $111111111/9 = 12345679$. Since 9 times 12345679 is 111111111, a multiplier of $9n$ (where $n$ is a digit) is sure to give a row of $n$'s.

Dividing a row of 1's by integers other than 9 until the quotient has no fractional remainder produces other "magic numbers." For example: $111111/7 = 15873$. Multiplying 15873 by $7n$, where $n$ is a digit, produces a row of $n$'s. Again: $111111/33 = 3367$. Multiply 3367 by $33n$ and you get a row of $n$'s.

A trick I call the Arabian Nights Mystery, because it is based on the properties of 1,001, begins by asking someone to think of any three-digit number, *ABC*. Tell him to repeat the number to make *ABCABC* and enter the six-digit number in the calculator. While he is doing it, stand with your back turned so that you cannot see what is going on.

"I'm beginning to get some vibes," you say, "and they tell me that your number is exactly divisible by the unlucky number 13. Please divide by 13 and tell me if I'm right."

Your companion makes the division. Sure enough, there is no remainder.

"It's strange," you continue, "but my clairvoyant powers tell me that the number now on display is exactly divisible by the lucky number 11." He makes the division. You were right again.

"Now I have a strong impression," you continue, "that the number on display is exactly divisible by the still luckier number 7." This proves to be the case.

Tell your companion to take a good look at the readout. It is *ABC*, the number he first thought of.

The trick cannot fail. Multiplying any three-digit number *ABC* by 1,001 obviously produces *ABCABC*. Because the prime factors of 1,001 are 13, 11 and 7, dividing *ABCABC* by those three numbers must result in *ABC*.

One of the oldest and still one of the best of all number-guessing tricks is particularly interesting because it introduces a celebrated theorem that goes back to a book on arithmetic written in about the first century by a Chinese mathematician and poet named Sun-tsu (or Sun-tse). One of the book's problems is to find the smallest natural number (positive integer) such that when it is divided by 3, 5 and 7, the remainders are respectively 2, 3 and 2. Sun-tsu supplies the answer, 23. He also gives, in verse, a general rule that he calls the *t'ai-yen* (great generalization) for solving the problem.

It is hard to believe, but at about the same time a famous Greek mathematician, Nicomachus of Gerasa, included exactly the same problem in his book on arithmetic. What is more, he gave the problem as a number-guessing trick. Someone is asked to think of a number from 1 through 100 and to divide it respectively by 3, 5 and 7, telling you only the remainder after each division. Knowing the three remainders enables you to name the chosen number.

The same trick, except that the divisors are 5, 7 and 9 and the number chosen is from 1 through 315, appears in the medieval arithmetic (1202) of Leonardo Fibonacci, the Italian mathematician for whom Fibonacci numbers are named. Tricks of this form were popular throughout the Middle Ages and the Renaissance. They can be presented with any number of divisors provided that they are relatively prime (have no common divisor) and that the chosen number is not greater than the product of all the divisors. (The divisors themselves need not be prime. For example, they could be 3 and 4, with the chosen number ranging from 1 through 12.) Since a pocket calculator makes for fast computing with divisors larger than digits, let us see how the trick operates with 7, 11 and 13, our lucky and unlucky numbers. Their product is 1,001, and so we can safely ask someone to think of any number from 1 through 1,000.

The trick is most effective if no one knows you are using a calculator. Hand someone a pencil and paper and then cross the room and sit with your back toward the spectators. Surreptitiously take the calculator out of your pocket and use it on your lap.

Ask your companion to think of any number not greater than 1,000, divide it by 7 and tell you the remainder. He repeats this procedure twice more, dividing the original number by 11, telling you the remainder and then dividing the original number by 13 and telling the remainder. How do you calculate the selected number?

Let $a$, $b$ and $c$ be the three remainders. The chosen number is the remainder after making the following calculation:

$$\frac{715a + 364b + 924c}{1{,}001}.$$

The three coefficients should be memorized or written on a small strip of paper pasted on the calculator. These are the simple steps you follow:

1. While your companion is dividing his chosen number by 7, enter 715. Multiply it by the announced remainder. If your calculator has no memory key, you will have to jot down the product and also the next two products so that you can add them later. If your machine has a memory that allows chain addition, enter the product in the memory.

2. While your companion is dividing his chosen number by 11, enter 364. Multiply by the announced remainder and add it to the preceding result.

3. While he does his final division by 13, enter 924. Multiply by the announced remainder and add to the preceding sum.

The number now in your readout is equal to your companion's chosen number modulo 1,001. If it is less than 1,001, it is the number. If it is greater, reduce it to the chosen number by repeatedly subtracting 1,001 until the number on display goes below 1,001.

How was the formula derived? The derivation is best explained with an example, and so let us use Sun-tsu's simpler version. The divisors are $a = 3$, $b = 5$, $c = 7$, and


*Calculator and area for subtraction*

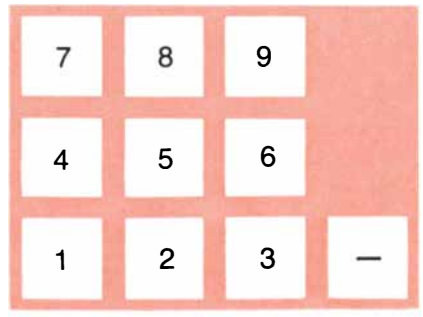
the chosen number must be no greater than 105.

The coefficient of $a$ is the lowest multiple of $bc$ that is one more than a multiple of $a$. There are rules for finding this coefficient, but when the divisors are small, as they are in this case, it is easy to get the number by inspection. Simply go up the multiples of $bc$ (35, 70, 105, ...) until you come to a multiple that has a remainder of 1 when it is divided by 3. The multiple is 70.

The other two coefficients have similar forms. The second coefficient is the lowest multiple of $ac$ that is one more than a multiple of $b$. It is 21. The third coefficient is the lowest multiple of $ab$ that is one more than a multiple of $c$. It is 15. We can now write the formula:

$$\frac{70a + 21b + 15c}{105}.$$

The number below the line is $abc$. This




*Three-by-three array for keyboard game*

ancient version of the trick (almost 2,000 years old) is the one most popular today with mathemagicians. It accommodates a chosen number from 1 through 100, and the formula is simple enough so that with practice the calculations can be done in the head. The mental steps can be simplified by replacing $70a$ with $-35a$, since $-35$ is equal to 70 modulo 105. This procedure also keeps the total lower, so that fewer subtractions of 105 are needed to reach the chosen number.

The remarkable theorem behind such tricks is called the Chinese Remainder Theorem in honor of Sun-tsu. In general it states: Given a set of relatively prime natural numbers greater than 1 $(d_1, d_2, \ldots, d_n)$ and a corresponding set of natural numbers $(r_1, r_2, \ldots, r_n)$, there is a unique number modulo $x$ (where $x$ is the product of all the $d$ numbers) such that, when it is divided by $d_i$, the remainder is $r_i \pmod{d_i}$ for every value of $i$.

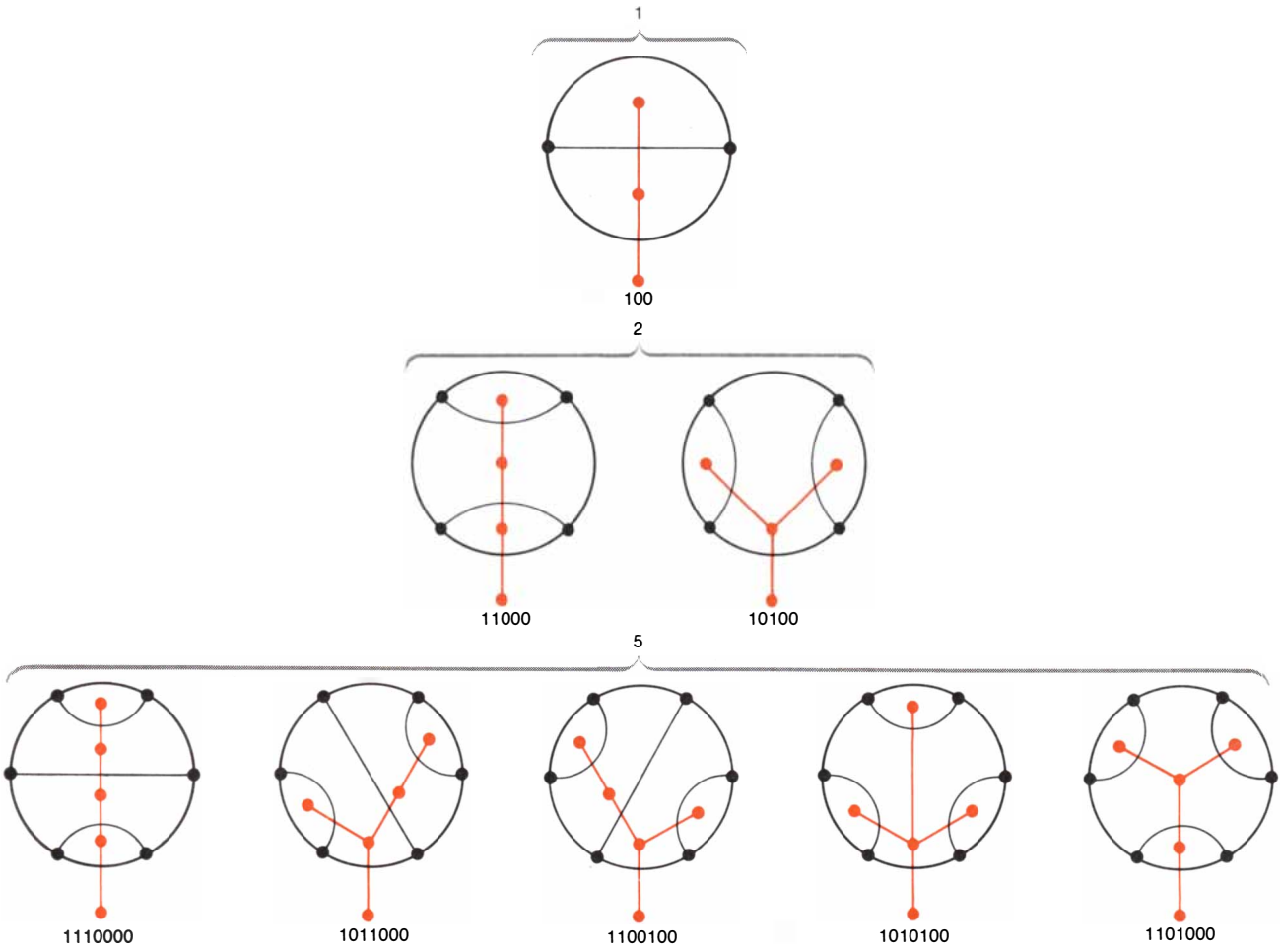
This is one of the most valuable theorems of congruence arithmetic. It serves not only for proving deeper theorems but also for answering many practical questions. Early astronomers and astrologers employed it for solving problems concerning solar, lunar and planetary cycles. Oystein Ore's *Number Theory and Its History* gives several applications of the Chinese Remainder Theorem to ancient puzzles as well as to a systematic procedure for the splicing of telephone cables. In 1967 Elwyn R. Berlekamp used the theorem in developing a fast algorithm for the computer factoring of polynomials. (A useful reference is Section 4.6.2 of *Seminumerical Algorithms,* Volume II of *The Art of Computer Programming,* by Donald E. Knuth.)

Another remarkable number theorem, which goes back to Fibonacci, underlies a prediction trick recently proposed by Francis T. Miles. Write the numerals 1, 6 and 8 on a piece of paper and turn it face down without letting anyone see what you wrote. Someone now uses the calculator to generate three "random" digits by the following method. He writes down any number he likes and writes below it any second number. Below that he puts the sum of the two numbers. The third number (the sum) is then added to the second number to get a fourth. This procedure is continued (each time by adding the last sum to the preceding number, using the calculator when the numbers get large) until the list has 20 numbers. Tell your companion to divide the last number by the preceding one, or vice versa if he prefers, and to take note of the first three digits of the decimal fraction. They are almost certain to be the three digits you predicted.

The trick works because in a generalized Fibonacci sequence, which is what the spectator is generating, the ratio between adjacent terms approaches the golden ratio, 1.618033..., as a limit. It does not matter which number is divided by which because the reciprocal of the golden ratio is .618033.... A magician I know likes to predict four decimal digits by placing four playing cards face down on the table. After turning over a six, an ace and an eight he looks crestfallen, as if he had missed on the fourth digit, since there is presumably no zero card. Then he turns the fourth card to reveal a blank face. If the fourth digit is not zero, he says, "As you see, I don't take chances."

No article on play with pocket calculators would be complete without mentioning the recent proliferation of whimsies exploiting the fact that most of the readout digits resemble letters when they are viewed upside down. Magic magazines were the first to publish such jokes, but they became widely known only after they were discussed in *Time* (June 24, 1974, pages 56–58). The procedure is to ask a question and then give a series of computations to produce a result that spells the answer when it is inverted.

The earliest of these upside-downers seems to have involved questions about who




*Correspondence between nonintersecting chords and planted trees*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Dodge

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won a certain skirmish between Arabs and Israelis. After punching in the relevant information one got the answer: 71077345. Inverted it spells SHELLOIL. Knuth devised the most mathematically interesting story line: 337 Arabs and 337 Israelis battle over a square property 8,424 meters on a side. Naturally we sum the squares of 337 and 8,424. Is there another way to obtain 71077345 as the sum of two squares? Yes, there is just one additional way: $5,324^2 + 6,537^2$. A paperback dealing entirely with such inversions has been published: *Calcu/Letter,* by Dan Steinbrocker (Pyramid Publications, 1975).

My bluish contribution to this useless pastime has appeared only in magic periodicals. What do Congress and belly dancers have in common? Multiply the prime number 2,417 by the number of months in the year, divide by the number of letters in "Congress," then multiply by the number of letters in "George Washington." Turn the machine around to read the answer. For greater precision, add 1.0950 and subtract .1776.

Last month's problem was to show that if $2n$ spots on a circle are joined in pairs by nonintersecting chords, the number of ways of doing so are counted by the Catalan numbers. The illustration on page 128 shows how Frank Bernhart establishes a one-to-one correspondence of the chord patterns with planted normal trees of $n + 1$ edges. It also gives their binary numbers. Since these trees are counted by Catalan numbers, as I explained last month, the same sequence counts the chord patterns. To make the diagrams easier to interpret, the small chords are shown curved.

Imagine that the circles and chords are elastic strings. Break each circle at the top and bend it into a straight line. The chord problem then becomes: $2n$ points on the line are paired in all possible ways by joining them with curves above the line that do not intersect. This is equivalent to finding all "planar rhyme schemes" for $2n$ lines that consist of $n$ couplets, allowing coupled lines to be separated by other lines.

If the line is now closed by bringing its ends together *below,* we get an inside-out version of the original problem. It could represent a lake with $2n$ houses on the perimeter, paired in all possible ways by nonintersecting paths. (All paths joining a given pair of houses are assumed to be the same; think of each pair as being joined by an elastic string that can be lifted up, stretched or shrunk and replaced anywhere on the plane outside the lake.)

To obtain the binary numbers imagine a worm at the bottom of each circle, inside the circle and facing west. As the worm crawls clockwise around the circle it calls out 1 when it encounters a chord for the first time and 0 when it encounters a chord a second time. The procedure works in reverse. Given the binary number, the worm labels the spots 1 and 0. There will be only one way to join each 1 to a 0 without an intersection of chords.

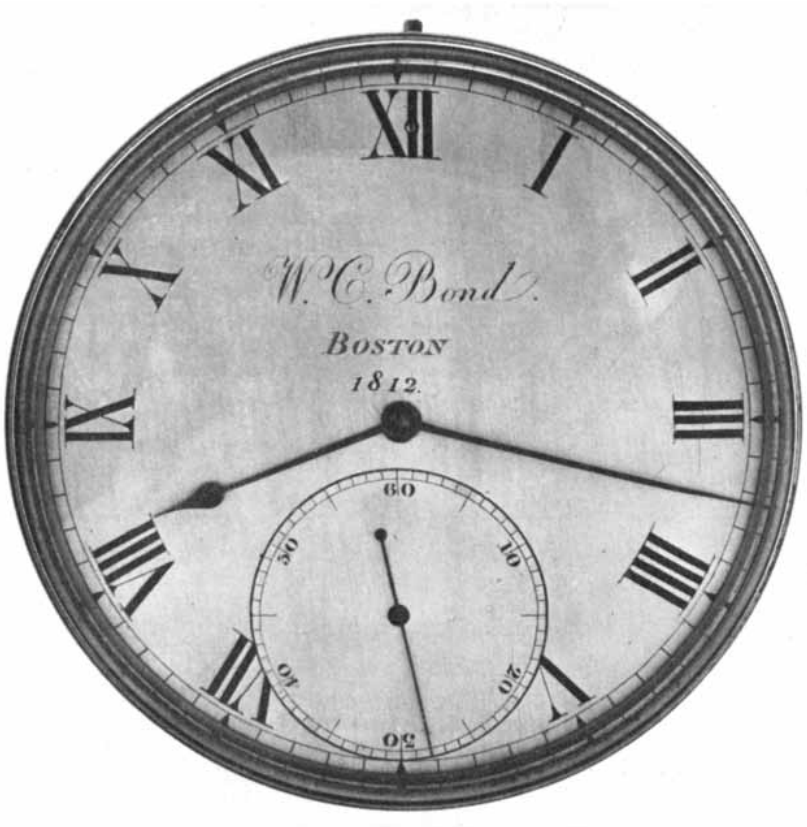
# BOOKS

## *American instrument makers early and late, and the art of piloting the big jet airplanes*

by Philip Morrison

THINKERS AND TINKERS: EARLY AMERICAN MEN OF SCIENCE, by Silvio A. Bedini. Charles Scribner's Sons ($17.50). WORLD ARMAMENTS AND DISARMAMENT: SIPRI YEARBOOK 1975, Stockholm International Peace Research Institute. The MIT Press ($25). It is now 200 years since the English colonies precariously planted up and down the Atlantic coast became "of Right... Free and Independent States," but the history of those colonies was itself not much shorter than two centuries by the time of the first Glorious Fourth. They were initially settled in the same half-century in which Gilbert, Galileo and Pascal were placing the cornerstones of modern science, and they grew through the times of Newton and Watt.

There were a few Colonial scientists of distinction, in the end even one or two of preeminence; Franklin was recognized in his day as the equal of any electrician of Europe. A string of well-known naturalists richly reported the life forms of the New World. There was a third branch, humbler in purpose and scope and yet numbering men of energy, originality and skill who are chronicled and celebrated by this apt and interesting volume. They were the "mathematical practitioners," those who aimed at the practical, everyday application of optics, of geometry from trigonometry to conics and of the techniques of engraving, dividing and lens grinding—all new. They made the maps and the plates, marked the boundaries, conned the ships on coast and ocean, used compass and vernier; they understood projections, orbit elements and the measurement of time. Land surveyors, mapmakers, navigators and the rest, along with the small firms that made the instruments indispensable to those tasks and the teachers who wrote the books and recruited such men from a farming population, are Bedini's actors. He claims no comprehensive work. Their number is too great, their individual acts are too small; their memory is fragmented among the few instruments and maps that survive, the proud advertisements they once placed in the contemporary press, the local archives and provincial publications that hold the scattered material. This lively book is an overview, a valuable guide to the literature and an interesting photographic museum of their work. About a fourth of the photographs come from the great collection in the National Museum of History and Technology of the Smithsonian Institution in Washington, where the author serves as deputy director.




*Dial of the first American-made chronometer, from* **Thinkers and Tinkers**

The book has 18 chapters and is mainly a brief, well-documented chronological narrative of the several periods of British North America, with an occasional more thematic chapter. The practical sciences were perforce based on English precept and practice. The Colonials were untrained, but they proved themselves equal to the task of self-improvement, adapting the methods and devices of London and Bristol to their own needs.

One case is the mariner's sextant. The precision angle-measurer in most general use at sea from the middle of the 18th century up to our day, it is a direct minor modification of Hadley's octant. It was in 1731 that John Hadley published his ingenious design of an accurate device to bring a directly viewed star into visual coincidence with a mirror image of, say, the horizon. In the previous year, however, a model of that same device had been successfully tested by a skipper out of Philadelphia for a young self-taught glazier-plumber-inventor of that city, Thomas Godfrey. (Ben Franklin, printer, had once taken lodgings with the Godfreys.) The English gentleman-inventor was anticipated by the Colonial artisan. An alternative design by Hadley proved more practical in one detail, and so to Hadley went the patent, the sales, the eponym and the popular acclaim. Historians today quite generally regard the credit as shared. "It often happens that the true author... lose the credit thereof and from age to age it passes to the name of another. Thus it happened heretofore to Columbus and many others; and this also has happened to a native of Philadelphia." So complained *American Magazine and Monthly Chronicle* in 1758.

The Colonial artisan-enterprisers formed no guilds, sought few specializations. They worked in any material suited to their ends, whereas the bigger instrument trade over in London split into branches of workers in brass and workers in wood. Indeed, brass was hard to get, a British monopoly based on English zinc carbonate and Welsh copper. Quadrants were made in Boston and New London of carefully pieced tropical hardwoods from the West Indies, particularly "green ebony" (Jamaican granadilla

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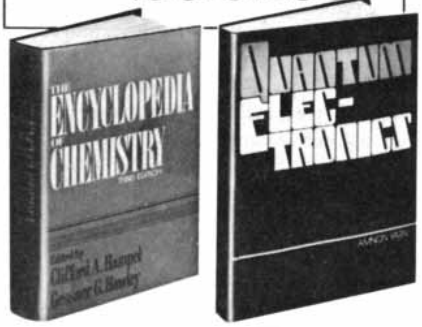


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wood), close-grained and well protected by its natural oils against the sea air and salt water that made iron or New England black walnut or fruitwoods less desirable. Brass production did not begin in Connecticut until the 1830's.

A revolution required maps. General Washington reminded the Congress in 1777 that "a good Geographer to Survey the Roads and take Sketches of the Country where the Army is to Act would be extremely useful." The British had plenty of good maps and a corps of engineer officers and draftsmen trained in the Tower of London. Robert Erskine was appointed Geographer-Surveyor of the Continental Army within 10 days after Washington's letter. Before Erskine's untimely death in 1780 he and his corps of surveyors had made about 130 maps, mostly rough plane-table products. He reported in 1780: "In short, from the Surveys made... I could form a pretty accurate Map of the four States of Pennsylvania, New Jersey, New York and Connecticut." These were in the end compiled on a grid based on a prime meridian at New York City.

The new nation needed maps and careful bounds for orderly expansion. The disputed boundary between Lord Baltimore's colony and that of William Penn had been fixed carefully on the ground a generation earlier (with errors verified in this century at only two or three degrees) by a pair of imported English experts, Charles Mason and Jeremiah Dixon, who brought along English instruments of unusual sophistication. By Thomas Jefferson's presidency a zenith sector like theirs (but made by two Americans, David Rittenhouse and Andrew Ellicott) was fixing the boundaries down south and "in the western Country" beyond Buffalo. Americans did not look back; they were feisty and confident and their skills increased with their own high self-estimate. Joseph Pope, an ambitious and learned clockmaker of Boston, spent years building an ornate outsized orrery more than six feet in diameter, perhaps "the most elaborate piece of scientific apparatus constructed in America up to that time." A state lottery was held in Massachusetts to raise money so that Harvard might gain the touted marvel. There it still is, a flashy gilt-and-mahogany lemon so poorly designed that it never worked.

"What may we not expect from this harmony between the sciences and government!" wrote Benjamin Rush. "Methinks I see canals cut, rivers once impassable rendered navigable, bridges erected, and roads improved, to facilitate the exportation of grain. I see the banks of our rivers vying in fruitfulness with banks of the river of Egypt. I behold our farmers nobles, our merchants princes."

Dr. Rush was farsighted; it has all come to be true. The ironies of history nonetheless bar any simple pride in our princely merchants and noble farmers. In the South Bronx or out at Pine Ridge, to name only unarguable examples, the dreams of the Yankee Enlightenment seem hollow. It is facile to blame that on thinkers and tinkers, one might maintain. But the 10,000 elegant single-axis gyros precessing slowly in the underground silos or in sleek tubes undersea are the handiwork of the manifest inheritors of those mathematical practitioners, now to be found in clean rooms from Newport Beach to Rocky Flats and Cambridge. Together with their counterparts between the Neva and the Pacific they hold the world uneasy hostage. The facts behind the ceaseless growth of more formidable weapons are yearly reviewed by the analysts of the Stockholm International Peace Research Institute (SIPRI), mainly on the basis of material from newspapers, the aerospace trade journals and official Government documents. They present this material in book form: a more or less unique study of the largest of all high-technology industries, worldwide.

This year's issue, which reviews the race up to the end of 1974, signals the advent of a new country, India, as the latest nuclear entrant and also marks the clear rise of a counterforce strategy by the hundred-armed U.S. Technically the most novel chapter is an account of reconnaissance satellites. The analysis "suggests that a ground resolution of 15 cm is feasible." Working from private observations (apparently made by the students and staff of an English grammar school), the report maps the ground tracks of Russian and U.S. satellites during the Cyprus conflict and at about the time of the Indian nuclear test. The conclusion is drawn that satellites are now maneuvered from the ground to monitor crisis areas "as a matter of routine" by both powers. The volume contains much information, technical, military and legal. The words of SIPRI's director, Frank Barnaby, are cogent: the big powers must expect more proliferation until they "show by their actions that they see no utility in nuclear weapons.... The only way is to reduce their nuclear arsenals." What can the Tricentennial expect?

HANDLING THE BIG JETS, by D. P. Davies. Civil Aviation Authority, Aviation House, 129 Kingsway, London (£3.50). "Airline flying really is money for old rope most of the time; but when things get hairy *then* you earn your pay." This cheerful, analytic, wonderfully knowing book by the chief test pilot of the U.K. Airworthiness Authority is aimed at the thoughtful professional pilot who wants preparation for the worst at the level not only of the what and the how but also of the why. A technically alert jet passenger will find it rewarding even if he is no engineer but simply a reader able to follow graphs and the conclusions they imply past a somewhat daunting barrier of acronyms and symbols of art (which are most of the time made clear by a careful glossary). No question of it: the flight deck of that plane is not only a gleaming display of instruments but also the workplace of a crew that operates a complex system by more than rote and feel.

The text begins with an account of why jets are different. They carry more momentum, much more than piston planes in both factors: weight and speed. The biggest civil jet, the 747C, has a maximum takeoff weight of about 350 metric tons. (That mass changes in flight by a factor of up to two as fuel burns!) The jet turbines give a comparatively small mass of air a much greater steady acceleration than the large propeller engines did. The turbines are powerful, reliable, efficient and cool, but they make no slipstream to give extra lift and they can change speed only gradually. The big control surfaces and high airspeeds demand servo-powered controls, and so artificial-feel feedback systems are necessary. They work well; a good one is "so good that the pilot has no indication that there is a servo system between him and the surface." A total feel-failure is bad news, but it is "a most remote possibility." The 747 controls, for example, are praised here in the most effective way, with a foldout sheet bearing the flow chart of the four separate hydraulic control systems. In that area the well-engineered 747 is "an order better in terms of redundancy and failure survival than any current airworthiness level would require." Civil jets are designed to the double-failure standard more or less across the board.

The clean form of the jet-transport wing—thin, swept back and not unusually long—means that it offers poor lift at low speeds. At low speed the drag actually increases faster than the lift as the speed decreases, and "the aeroplane will quietly slide up the back end of the drag curve." That is the reason for the elaborate system of leading-edge and trailing-edge flaps, more often seen through the cabin windows than by the officers up front. The high-performance swept wing and the high-set tail plane and rear engines can lead to a nose-up superstall (carefully explained here with many graphs and drawings and a simple formula), from which at best an extremely large loss in height is bound to occur. ("It cannot be put too strongly. Whatever you do, *don't stall the aeroplane*.")

Unable to provide enough natural aerodynamic stability and timely prestall warning behavior, the jet designers have built prevention into the controls. Some pilots "cannot stand the thought of a stick pusher," but pushers are generally in use, they work well and they confer virtually "immaculate stalling qualities." One such system is described and diagrammed. The sensor is a duplicated set of vanes in the airstream near the wing. Reliably powered by nitrogen stored under high pressure, the system responds promptly to a change in flow, shakes the stick to warn the pilot, blows a strident klaxon and in due time pushes the stick strongly forward, nosing the aircraft down sharply. The design is biased strongly toward not pushing when pushing is not required. The reason is that erroneous operation would put the airplane at clear risk of nosing right into the runway during those 10 seconds of approach when the plane is between about 120 feet high (too low to allow pilot countermeasures)

*A Boeing 727 shortly after takeoff, with its triple-slotted trailing-edge flaps extended, from* **Handling the Big Jets**

and 10 feet high (when the penalty is only a hard landing). The overall probability of such a mishap is about one in 36 million approaches. "This we just have to live with. The problem is far less than the normal risk of an accident resulting from any single cause."

Jets "lift off" ("come unstuck" in British English, according to the little English-American aviation phrasebook included here) at high speeds. That means a lot of energy wasted by transfer to any water, snow or slush on the runway. The matter is discussed in interesting detail. Runway conditions, like severe weather aloft, require a captain to understand and to decide, unaided by designer or ground control. Crude measurements of the depth and density of the runway slush and of the speed costs of drag are the elements that shape his decision. Thus is tested command character, the ability to make the essential quick response to a complex problem with the data uncertain and the stakes high. A commander has the choice: he can delay or divert. Let the competitors care for themselves. ("If you should bust something, the fact that someone else got away with it a few minutes before or after will be little consolation.")

Severe weather aloft is the final test of designer and pilot. The jets are designed to withstand gust speeds at altitude that are rather reduced from their low-level values, walking the prudent line between speeds high enough to avoid stalling and low enough so that all parts of the plane can withstand the gust forces. "Inspired estimations" for the limits, made by structures experts on the basis of World War II experience, remain valid; all recent flight-recorder results support their choices: vertical gust speeds of 45 miles per hour (corrected for air density) are still the design standard. Turbulence can cause gross upsets, knocking out the main altitude indicators. Here too the prepared and prudent captain earns his pay. "*The inverted dive* will be obvious by all the loose equipment flying around the flight deck"; the remedy is to roll 180 degrees, and promptly.

What else can happen? Consider hail. There can be severe damage when the stones are more than two inches in diameter; that condition is encountered by some unfortunate aircraft worldwide about four times a year. One should not fly under thunderstorms. "When the awful battering starts, there is no means of establishing the size of the hail." One should not turn away from that assault if one hits it suddenly; the "quickest way out is straight on." The cabin may suddenly decompress. Then to the other problems is added the cloud-chamber effect, as the quickly oversaturated air of the cabin and flight deck becomes a dense cloud. It is not serious—if you expect it.

Here is what can happen (Davies is reporting on what a pilot called the most violent jolt "in over 20,000 hours of flying"): "I felt . . . a buffeting . . . one might expect to encounter sitting on the end of a huge tuning fork that had been struck violently. Not an instrument on any panel was readable . . . white blurs against their dark background. . . . Briefcases, manuals, ashtrays, suitcases, pencils, cigarettes, flashlights flying about like unguided missiles. . . . My seat belt was tight . . . briefcase was on the ceiling. . . . We acted in unison applying as much force as we could gather to roll aileron control to the left. . . . The air smoothed out and we gently leveled off at between 1,400–1,500 feet."

Chief Pilot Davies is truly a man for all seasons. One comes away with a new respect for jet captains and crews. They need the famous seat-of-the-pants experience and reflexes, and no less the stout heart of command. This book, accessible to the nonspecialist, makes it evident how much they depend as well on a personal enthusiasm for the job that ensures a variety of rational processes of analysis that are carried out in thought, well in advance of that next engine failure or turbulent cloud.

WORK AND PLAY: IDEAS AND EXPERIENCE OF WORK AND LEISURE, by Alasdair Clayre. Harper & Row, Publishers ($11). "The silence of the past—for any but the words of the rich, the powerful, or the clerical—is vast: those whose lives we would need to know about . . . spoke; they did not write; and their words have gone." Brecht inquired more elliptically: "Who built Thebes of the seven gates? / The books give the names of kings. / Did kings heave those blocks of stone?"

This unusually penetrating small volume of social analysis cleaves into two parts. In the first half the young English scholar-pro-

ducer analyzes from the texts certain views expressed by the big names—Rousseau, Schiller, Hegel, Marx, Morris and their modern continuators; in the second he turns to the rich vein of folk song in an attempt to bring as testimony out of the past some of the thoughts of the unrecorded people who handled rope and shuttle, scythe and hammer.

The question he addresses is important: Can human work bring its own reward? Was there a time—be it in a savage society or before capitalism or before machines or before factories—when "the ordinary experience of most men at work was dramatically more happy and satisfying" than it is now or has been over the past couple of centuries? People are asking this question seriously everywhere today, on the assembly lines of Volvo and Chevrolet, in the communes of the Vermont highlands, in the reports of sociologists and economists.

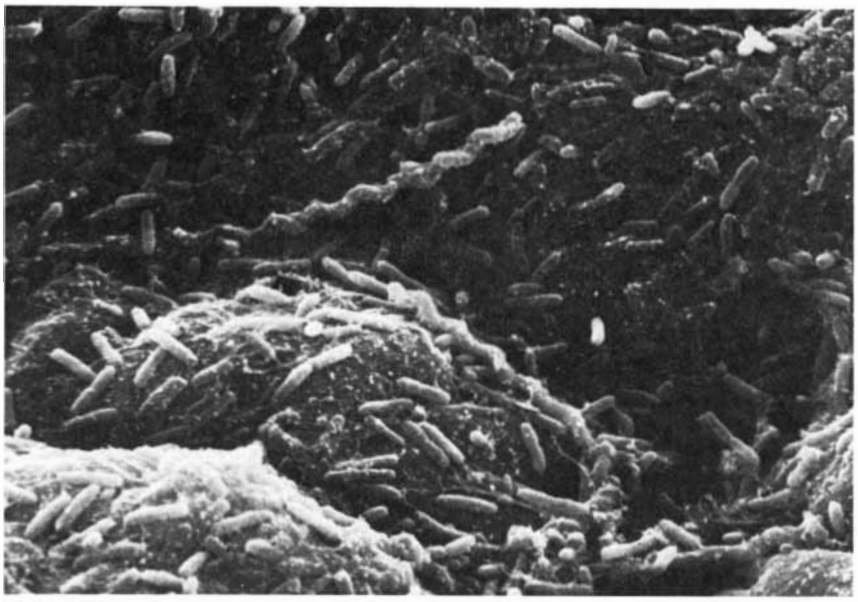
The philosophers were firm on the question. Rousseau would prefer for Émile the free craft of carpentry above all; monotony and dependence are equal perils; we must "diminish desires" and never follow a formula. The early Marx continued the critique. He saw in work the natural state of humanity, but in the end his thought is complex. Certainly he looked forward to a golden time when work would be social and not for an employer, would be varied and not permanently specialized, and would unite mind and hand. Yet his vision was closer than that of some other critics to the world of his time: he saw no clear evil in the factory itself, bitterly condemnatory of the capitalists' cruel mills as he was. In *Capital* Marx neither idealizes machines nor makes demons of them. Indeed, not even Morris, proponent of the artist-craftsman, was a consistent opponent of the machine. Looking one by one at these thinkers, with an engagingly critical tone, nowhere oversimplified, the author is led to a blunt question: Why have we nowhere found a society, socialist or capitalist, that "speaks a language" other than that of GNP, productivity and income? (Here the somewhat transient youthful dissent in the U.S. and Europe and the much wider example growing in the People's Republic of China have a claim to attention not given them in this work.)

Clayre wants to hear from the kind of people who dragged the stones to Theban gates, and he seeks their answer in song. He is quite aware of the limits of the method, of the varying claims to authenticity his lyrics make, and yet his account is fascinating. The people who worked long hours saw a virtue in play, play both out of hours and directly in the place of work. Work is often intensely social and even erotic. "Where are the girls? I'll tell you plain / The girls have gone to weave by steam." The songs rarely deal with the intrinsic nature of work but rather with friends, lovemaking, fighting and dying. Songs of complaint about monotony are often songs of complaint about injustice. "Poverty, poverty knock! / Me loom is a sayin' all day. / Poverty, poverty knock! / Gaffer's too skinny to pay." Work as a mere instrument toward pay is by no means uncelebrated. "It'll be bricht both day and nicht when the Greenland lads come hame, / Wi' a ship that's fu' o' oil, my lads, and money to our name." There are many more.

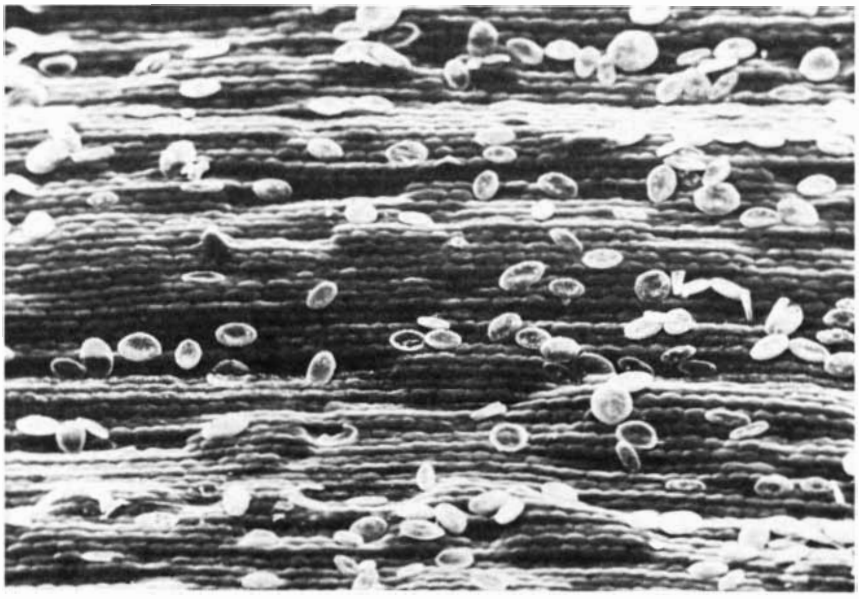
The praise of pure craftsmanship and even of art is not easy to find. Giotto might be regarded as a paradigm of the medieval artist, but he was not free of instrumental views toward his work. He "combined the highest artistic skills with an acute business sense. In 1314 four, perhaps even six, notaries were looking after his business interests." This may well bear out the argument that it was the dawn of capitalism that gave us the name of the artist; Giotto's predecessors for many centuries had not been so recorded. Clayre makes it pretty clear, however, that work seen as a means, not an intrinsic end, goes back to money and markets, long before the Industrial Revolution and its smoky power sources.

The happy time of gathering and hunting, was that the golden age of the love of work? The songs of the outrigger, of the lost pleasures of the dead, of the seal hunt or the stalking of the elephant do seem closer to the philosopher's ideal. Yet their burden too is often one of war, of love or of the sense of the life hunters share with their game. "Perhaps it is not the activity but the poetry of songs like this, together with ritual, that mainly distinguish hunting and gathering . . . from work in our time."

There is no neat conclusion here to this complex question, next after war and peace



*Bacteria and spirochetes* (corkscrews) *on decaying salmon tissue, from* **Microbial Seascapes**



***Diatoms on the surface of eelgrass, from* Microbial Seascapes**

perhaps the deepest issue of our days. Shorter hours, the addition of "leisure-like" elements to work and a sense of sharing and justice may be "more relevant to some trades than any attempt to improve the intrinsic nature of the work." Only a fortunate small minority in the past may have derived satisfaction from work done for its own sake. The reformers were not so much restoring a lost golden past as looking to a shift in the values of the people. "The conditions of satisfying work are not unknown, and there are ... real signs of response already to the idea that they should be extended, to be within reach of anyone who wants them. Perhaps a hundred years or so of failure are not very long in the time-scale of an idea like this."

GROWTH RHYTHMS AND THE HISTORY OF THE EARTH'S ROTATION, edited by G. D. Rosenberg and S. K. Runcorn. John Wiley & Sons ($57). On January 24, 1925, the band of totality of a solar eclipse included New York City. The southern edge of the path of totality crossed Broadway near 86 Street. "We know this because observers, untrained in eclipse observation, were set out at the rate of one per block along Broadway with a questionnaire to complete after the eclipse." Every observer north of 86th reported totality, everyone south denied it. The resolution was about 300 meters. Edmund Halley made inquiries similar to that for the eclipse of 1715, whose path across England he had predicted in advance, and he established the edge of the path to within one or two kilometers with a much smaller group of witnesses; at Cranbrook near the southern limit the sun was observed "to be extinguished but for a moment and instantly to emerge again." The effect of true totality is demonstrably striking, like "having a blanket thrown over one's head."

On such grounds the two authors of the final long paper in this remarkably diverse symposium examine the solar eclipses on record in the world literature up to modern times. They throw out the bulk of the 1,000 or more reports we know from Late Babylonian, Classical Greek and Roman, Chinese and medieval European history as failing to demonstrate clearly either totality, partiality or date. (They are generally willing to presume place once they can identify the eclipse from its date.) They retain less than a score of cases that give "no cause for doubting" totality on a given date at a given place and another dozen or so (before the 16th century) with some single element of uncertainty. The oldest "class B" example is from Ugarit on May 3, 1375 B.C. (with some possibility of dates a century or so away from that), where the tablet reads: "The Sun was put to shame and went down in the daytime, with Mars in attendance."

From these records the authors can extract the change in the spin rate of the earth and in the orbital motion of the moon. Their statistical treatment and careful discussion of the data lend confidence to this tour de force, of which they are only the latest performers. They show growing consistency in data and theory, which give some confidence that the day, for example, has grown longer by about 25 milliseconds in the past 1,000 years. (The eclipse seen in Babylon in 136 B.C. would otherwise have been total only in Britain.) The rate fluctuates, however; it is jiggling up and down half a millisecond or so every few years, and the steady slowing against the atomic clocks (considered in another of the papers here) has amounted to a couple of milliseconds over the mere 20 years since atomic time was first well kept.

Why? Tides surely drain the spin steadily and slowly by friction, and the effects produced by the patterns of winds and currents are certainly only seasonal. The rest is hidden deep within, an oscillating transfer of spin between the mysterious core and the mantle; the stuff of the earth may in the long run be settling, with the heavier material sifting down to the core. There is no lack of speculative proposals: gravity is weakening, affecting the earth's size and all orbits, or the oceans have grown greatly, or some spin changes are triggered by solar activity. These views and more are exhibited here in about a third of the 30 papers.

As for the rest, it is not geophysicists and astronomers or even historians who write but paleontologists and mollusk experts, together with an occasional botanist or physicist. In 1963 Professor John Wells of Cornell, a man learned in modern and fossil corals, pointed out that the growth lines in corals might preserve tide and daylight counts—daily, fortnightly, monthly and even yearly by seasons—and carry that trace along not merely for a few human millenniums but into the depths of geologic and galactic time, billions of years ago. One must look mainly to the sea, since no land life can be found much below the Devonian, a mere 400 or 500 million years back.

This symposium is really a current account (from a meeting early in 1974) of the battle for knowledge in the salient that Wells first attacked. The lines are fluid and the gains are few. There are plenty of layers and marks in shells, old and new, and it is not too hard to count them up. The techniques get better: there are electron microprobes for chemical characterization of the layers, there are fine analytic tricks with power spectra and the like and there are double-blind schemes to keep the investigator from fooling himself, and still the results are at best cloudy. People cannot find very clear rhythms in modern corals. Clams and scallops grown in laboratory tanks show a fairly complicated set of layers. Sometimes the shell develops clear laminations month after month—a fine clock and calendar—and then takes a holiday for some days at the end of the year, applying its energies to something other than shell growth.

The layered colonies of blue-green algae, called stromatolites, that span the whole of time from three billion years ago to the present with little evolutionary change are prime material. They show—perhaps—a Precambrian month of 26 days and a year of 800 or 900! So ancient samples of 50 consecutive years seem to indicate; there remains doubt. It seems fair to conclude at least that there was a moon in orbit around the earth three billion years back, in itself no mean conclusion. This is science in the process of growth: exciting, hopeful, talented, awkward, unsure.

MICROBIAL SEASCAPES: A PICTORIAL ESSAY ON MARINE MICROORGANISMS AND THEIR ENVIRONMENTS, by John McNeill Sieburth, with underwater photomacrography by Harold L. Pratt, and with the assistance of Paul W. Johnson and Donald Scales. University Park Press ($9.50). The beautiful tests of radiolarians, those perforate and spiny helmets dear to microscopists for a century, form a familiar frontispiece for this unusual, carefully planned atlas of the submarine lawns of bacteria and gardens of protozoans to be seen on the surfaces of the underwater world. We are shown that world clearly through the scanning electron microscope, with its remarkable depth of focus, at magnifications from 50 diameters or so up to many thousands. Careful index drawings explain what we are seeing; proper attention to establishing the shot as a good filmmaker does, here by photographs made at recognizable magnifications of from 10 to 20 diameters, sets the book apart from other such monographs and makes it more attractive.

We look at floating particles, at the surfaces of kelp and eel, at a plastic cup and braided nylon fishing line, at slate pebbles and rolling sand grains (which gather no micromoss). These are from coastal waters, but some others are from the depths. Nearly half of the photographs show the surfaces of living animals decked with the diverse forms of the kingdoms of life that choose to grow there. The tail of a salmon infected with tail rot is rich in filaments of fungus; the clean uninfected skin of the same fish is patterned like a maze but fully protected by some adaptive process from the populations of tiny forms that are found, like weeds and grass, growing almost everywhere. We look with respect at the business end of the fearsome shipworm, a rotary grinder a couple of millimeters across, at a magnification of 58 diameters. We see diatoms looking exactly like an African talking drum, quite free of bacteria. Here is the red-tide creature, made 12 centimeters across at an enlargement of 5,300 diameters. One 14-sided polyhedron with six spines, a photosynthetic flagellate, is perhaps the most symmetrical of all the forms; a hairy ciliate is the shaggiest. The mahogany trim and fiberglass hull of a derelict sailboat found north of Bermuda have suffered a sea change into a living microcosm that is displayed across a number of pages.

It would be ungenerous to omit mention of the designer and artist Sheila Humphreys and the artist Charles E. West, whose skill and taste have added much to the utility of this unpretentious volume.

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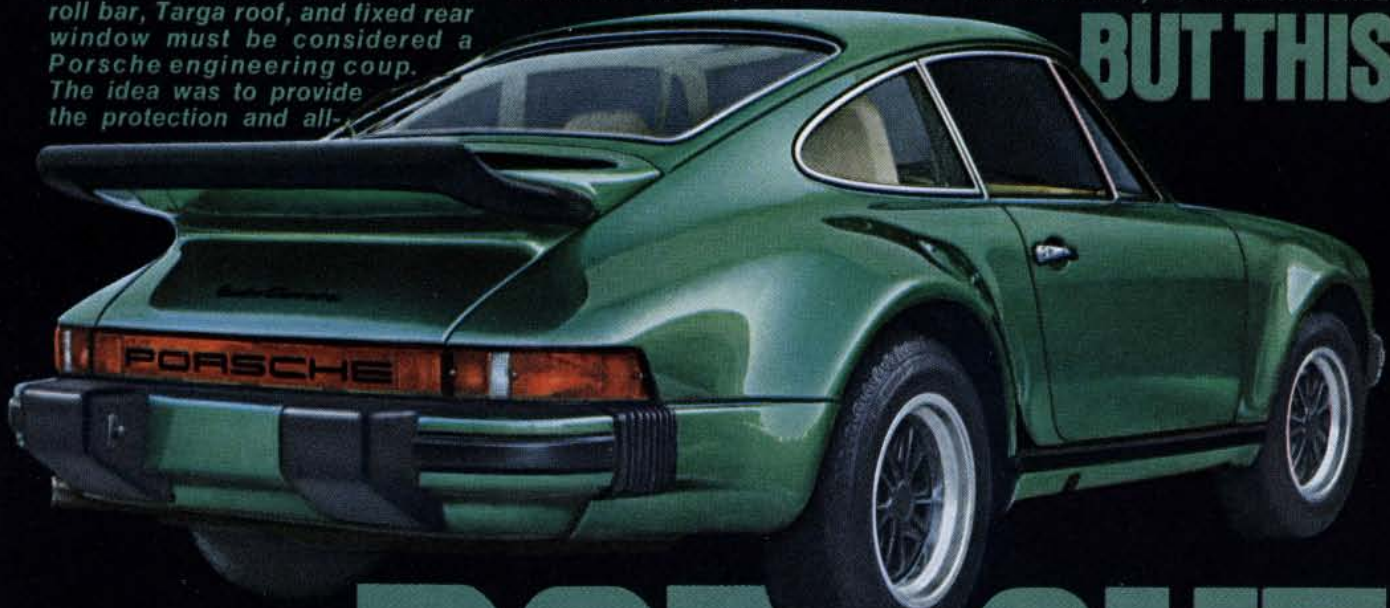


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