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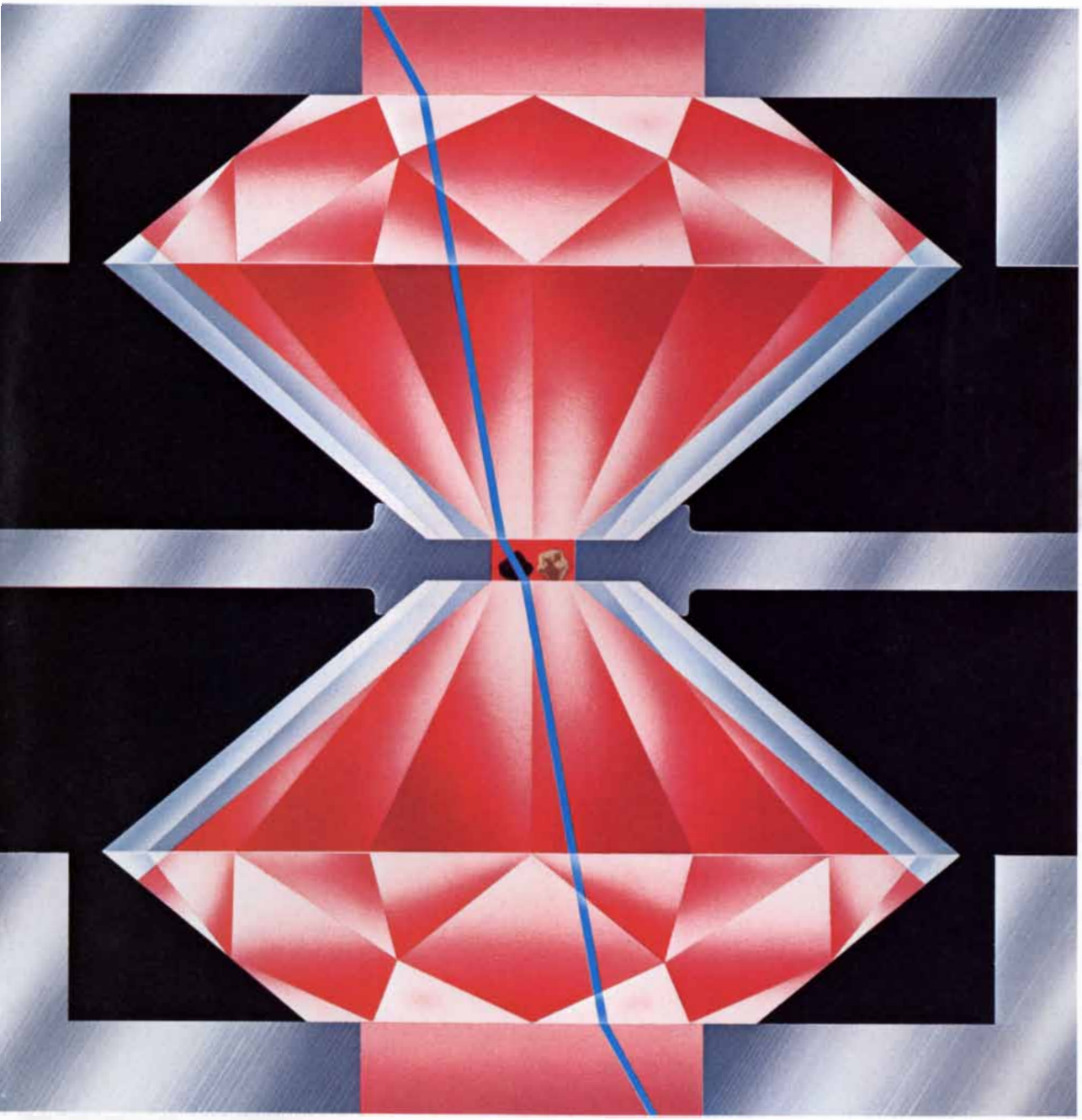

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April 1984

A HERITAGE OF

The C

At our family winery in the beautiful Sonoma Valley, we have for three generations produced wines in a style that complements food. It is part of our heritage and extends far beyond our eighty years in California to a small village in Northern Italy. It was in Farneta,

the birthplace of my grandfather, Samuele Sebastiani, that the dream for Sebastiani Vineyards was formed. It was this place that shaped and defined a style of winemaking that would become uniquely ours.

Top: The Monastery of Farneta, Italy. Below: Sam Sebastiani (left) during the 1983 Farneta harvest.

During the 1983 harvest, I joined the families of Farneta in the vineyards and rode with the grapes into La Certosa di Farneta, the 12th century monastery where young Samuele learned to make wine. Here, winemaking techniques have changed little over the centuries and the traditional pairing of these local wines with local foods is a source of great regional and family pride.

The heart of this richly colorful district is the ancient walled city of Lucca. There, my wife Vicki and I explored the many twisting streets and courtyards, with their dozens of markets and restaurants. As we walked, we came to fully appreciate that part of our heritage which began near this city a century ago.

Since my grandfather founded

Towers and rooftops of Lucca.

WINE AND FOOD

Origin

our winery in 1904, wine styles have evolved with changing tastes. We have, over the last few years, made many changes of our own in the vineyards and winery to produce wines of even greater elegance, complexity and finesse. But as we have made these changes, our original vision remains intact, "Wine and food and family and friends are the classic ingredients of a gracious dinner table." It is our respect for this tradition that will always direct the Sebastiani Vineyards style of winemaking.

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Vicki Sebastiani (center) in the Lucca marketplace.

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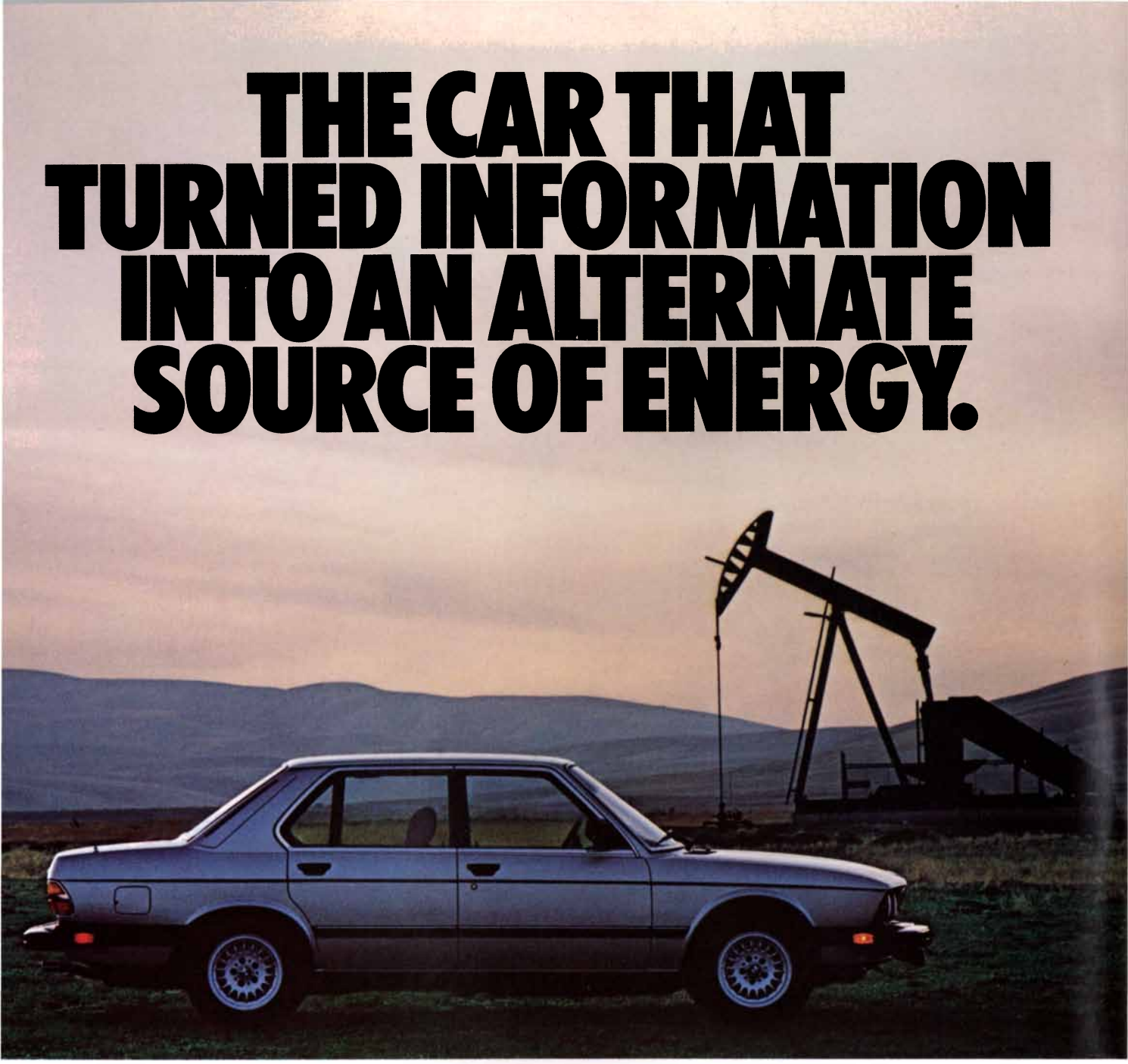

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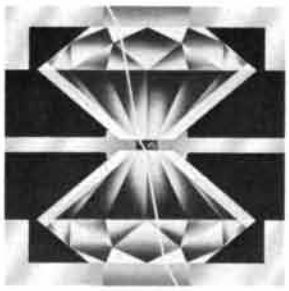

THE COVER

The painting on the cover shows the central mechanism of a new device that can generate pressures as high as those at the boundary between the core and the mantle of the earth: about 1.7 million atmospheres (see "The Diamond-Anvil High-Pressure Cell," by A. Jayaraman, page 54). Two gem-quality diamonds, each weighing about half a carat, are mounted in opposition to each other in order to generate thrust along the central vertical axis. At the center, between the two diamonds, is the high-pressure cell; it is a small hole drilled in a sheet of hardened steel, which is shown in cross section. The pressure applied by the diamonds indents the steel and causes it to extrude around the edges of the diamonds. Inside the cell is a crystal of samarium monosulfide, which changes from black to gold at a pressure of 7,000 atmospheres. A small red ruby is also shown in the cell. When a beam of blue laser light is focused onto the ruby through the transparent upper diamond, the ruby fluoresces a deep red. The wavelength of the fluorescence changes with pressure in a known way; by measuring the change on a spectrograph the pressure inside the cell can be determined. The thrust is transmitted to the diamonds by a mechanism that can be held in one hand and operated by hand-tightening a threaded bolt.

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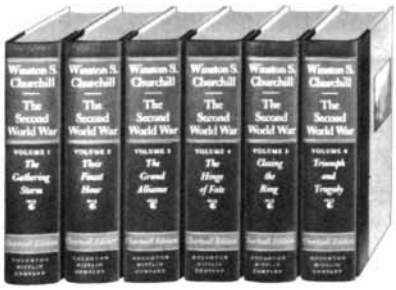

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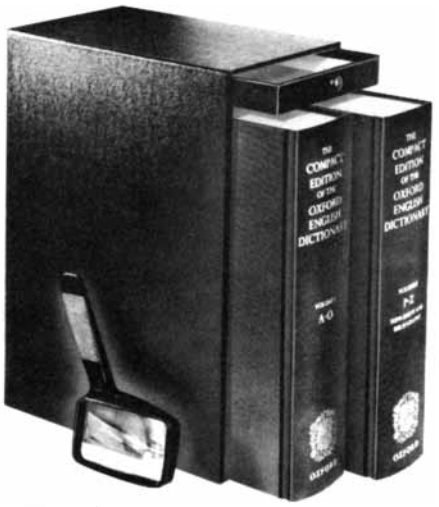

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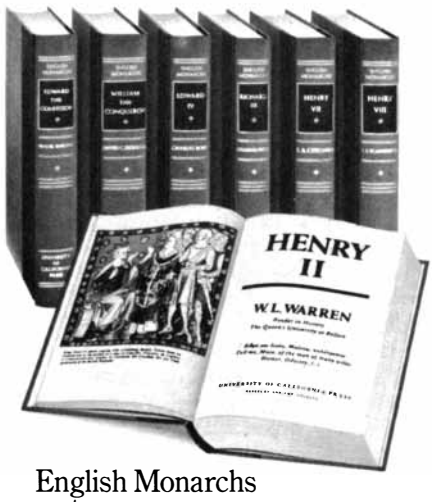

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LETTERS

Sirs:

Bryce S. DeWitt's article "Quantum Gravity" [SCIENTIFIC AMERICAN, December, 1983] raises two issues I feel are not being given the attention they deserve. The first of these concerns is that the pursuit of a quantum theory of gravity does not seem to be motivated by the same considerations as past physical theories were. Most if not all of the theoretical advances in physics came about because of a need to explain away some unresolved question that was directly related to experience or experiment. What is quantum gravity intended to explain? Professor DeWitt's only offering seems to be that "a consistent theoretical framework demands that the gravitational field itself be quantized."

Peter G. Bergmann, a worker in the field, offers three reasons for wanting to construct a quantum theory of gravity. They are: (1) "The great likelihood that if most physical fields are quantum fields, the gravitational field will be no exception." (2) "The expectation that a fully elaborated quantum theory of gravitation will be far more than a routine replica of other presently known quantum field theories." (3) "Finally, that any experience that we gain in striving to unify the principles of general covariance and of universal complimentarity may teach us something worthwhile about the limitations of either."

These are weak arguments for quantizing the gravitational field. There are, in my opinion, stronger arguments against it. One argument has already been stated: There is no experimental evidence demanding such a theory. In Professor DeWitt's own words: "Because experiment can offer no guidance, quantum gravity is unusually speculative." Another argument is the obvious difficulty of producing a satisfactory theory. I am not suggesting that Professor DeWitt has no right to pursue the question. My issue is that he is presenting the study of such admittedly interesting questions as a standard step in the progress of theoretical physics, when it is not. It is a mathematical exercise that may or may not relate to the real world.

The second issue, not unrelated to the first, is evidenced by Professor DeWitt's statement that "it is unlikely that individual gravitons will ever be observed directly." Today physics finds itself addressing issues such as the existence of gravitation, the state of the universe 10^{-42} second after the big bang and the occurrence of the big bang itself. These pursuits seem to be closer to philosophy and metaphysics than to physics.

I certainly do not suggest that thought on such subjects be discarded, but the fact that physics, as experimentally verified, has begun to thrust itself into realms where experimental verification may be impossible or quite meaningless deserves our attention. I am not accusing Professor DeWitt of being unaware of these issues. I suppose I am expressing disappointment that he did not address them. In my opinion they are symptomatic of a major change in the standard paradigm of physics and its philosophical underpinnings, but there does not seem to be any acknowledgment of this in the physics community in general. If I am correct, physics is going through a major metamorphosis and, if only for this reason, we should strive to keep our philosophical house in order.

EDMUND J. SULLIVAN

Naval Underwater Systems Center
Newport, R.I.

Sirs:

Mr. Sullivan is quite right to stress that theoretical physics has undergone changes in style and method in recent years. Whether these changes should be regarded as "major" or permanent, however, remains to be seen. It is true that the formalism and concepts of theoretical physics have become more remote from immediate sensory experience and that greater logical leaps are required between theory and application. Yet the acid test is and always will be the ultimate agreement of theory with experiment or observation.

The fact that there is no present experimental evidence for a quantum theory of gravity is not a strong argument against it. In the early 1930's there was no experimental evidence for renormalized quantum field theories, such as the modern theory of quantum electrodynamics. The existence of infinities in the formalism led some of the founders of quantum electrodynamics to propose mutilated versions of the theory. The discovery of the relative displacement (Lamb shift) of the spectral lines associated with the $2S$ and $2P$ levels in the hydrogen atom and of the anomalous magnetic moment of the electron showed that the elegantly simple original theory was right. It only had to be properly interpreted to become the most accurate theory known to physics. Moral: One should always attempt to push elegant theories to their extreme logical conclusions. In this way one discovers both their strengths and their limitations. That is what one is attempting to do with quantum gravity.

Let me take this occasion to correct a possible misunderstanding regarding my reference in the article to the invention of supergravity "by Daniel Z. Freedman, Peter van Nieuwenhuizen and Sergio Ferrara and (in an improved version) by Stanley Deser and Bruno Zumino." Several of my colleagues have reminded me that the Deser-Zumino form of the theory was viewed as an improved version for only a relatively short time. The two versions were quickly shown to be equivalent, but for various technical reasons the original Freedman–van Nieuwenhuizen–Ferrara version is nowadays used almost exclusively. This version was, of course, the first to be discovered.

BRYCE S. DEWITT

University of Texas
Austin

Sirs:

As an amateur bicycle racer of the hoary traditionalist sort I was intrigued by "The Aerodynamics of Human-powered Land Vehicles," by Albert C. Gross, Chester R. Kyle and Douglas J. Malewicki [December, 1983]. I think, however, the authors were a bit hard on the Union Cycliste Internationale in accusing it of stifling technological development. The UCI is no more interested in preventing people from racing streamlined recumbents than it is in prohibiting motorcyle racing; it has simply chosen to leave both activities outside its jurisdiction.

The UCI rule banning any device intended solely to reduce air resistance ensures that conventional bicycles are raced against other conventional bicycles, leaving it up to the athlete in the saddle to win the race. Just as springy baseballs can make ball games higher-scoring but no more exciting, so faster machines do not necessarily improve the sport of competitive cycling.

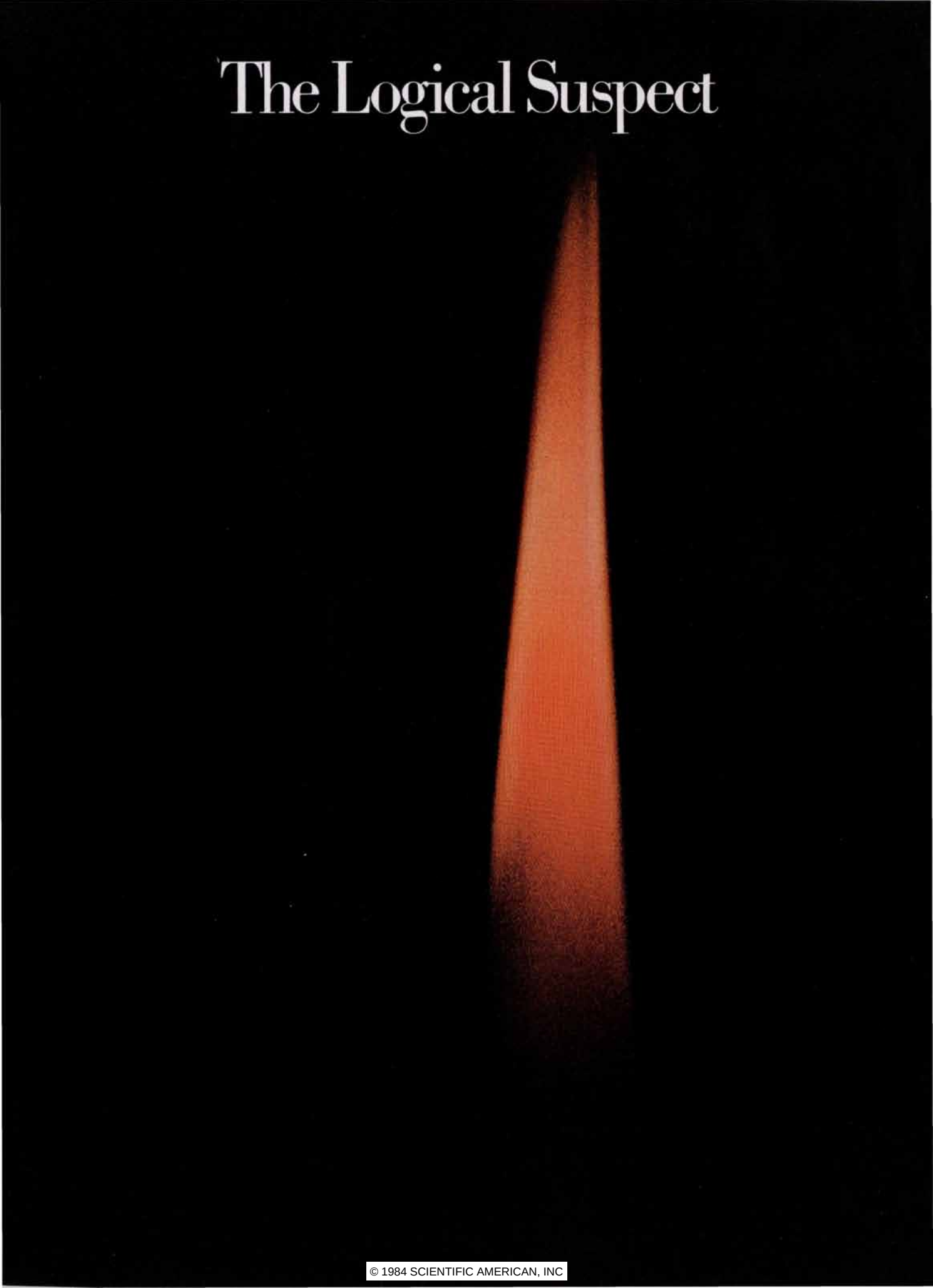
Rules define a sport and give it its identity. The International Human Powered Vehicle Association requires only that the machines be human-powered; its races, however, have been structured in a way that encourages the development of vehicles with certain peculiar characteristics. By holding its races on motor speedways the association has encouraged the evolution of HPV's that are superbly well suited to those tracks but quite unsuited to the cobblestones and mountain passes of the Tour de France.

Streamlined recumbent cycles had been developed by the 1930's. The reasons they never caught on for recreation or transportation include serious drawbacks inherent in the large fairings and the long wheelbase characteristic of the design. At the same time multiple gearing—the dérailleur—was developed and flourished even though it was banned from racing bicycles in the early years.

PAUL FOLEY

Brighton, Mass.

The Logical Suspect



The Logical Suspect

Soot particle growth as it takes place in wood-burning fireplaces, diesel engines, and industrial furnaces, has been attributed to a complex set of interdependent chemical reactions. A researcher at the General Motors Research Laboratories has demonstrated that the decomposition of a single species is primarily responsible.

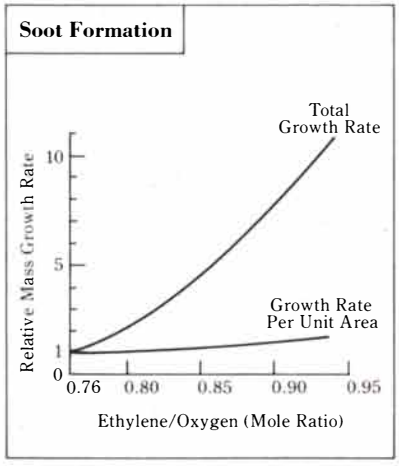


Figure 1: Total growth rate contrasted with growth rate per unit area plotted as a function of ethylene/oxygen mole ratio measured at a given height above the burner face.

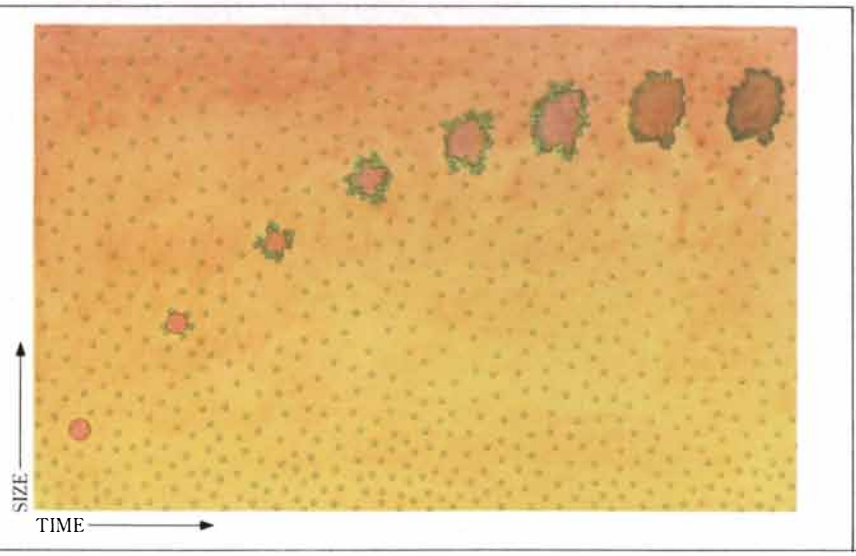


Figure 2: Artist's rendition of the surface growth of a single soot particle by the incorporation of acetylene molecules.

SOOT FORMATION may be divided into two stages. Microscopic soot particles are generated in the "inception" stage. They reach full size in the "growth" stage, which accounts for more than 95% of their final mass. Most scientific exploration has concentrated on particle inception which, despite all the effort, remains unexplained. Dr. Stephen J. Harris, a physical chemist at the General Motors Research Laboratories, has reversed traditional priorities. Combining experiment with logic, he has formulated the first quantitative explanation of the growth stage in soot formation.

Dr. Harris arrived at his mechanism through an elaborate process of elimination. To focus on the chemistry of soot growth, he began by eliminating from his investigation the complexities introduced by turbulence and mixing. He limited his research to premixed, ethylene/oxygen, laminar flames with one-dimensional flow.

Previous descriptions in the literature told him that two processes take place simultaneously during growth. Incipient particles collide and coalesce into larger particles, while growing at the same time by incorporating hydrocarbon molecules from the burned gases.

The first process reduces total surface area without changing total mass, while the second, called "surface growth," increases both total surface area and total mass. Hence, the increase in the total mass of soot can be entirely attributed to surface growth.

Dr. Harris set out to identify the hydrocarbon molecules—or "growth species"—responsible for surface growth. Increasing by increments the richness of the flame, he made the key discovery that although the total mass growth rate (gm/sec) increases strongly when the ratio of ethylene to oxygen is increased, the mass growth rate per unit surface area ($gm/cm^2/sec$) increases only slightly (see Figure 1). Thus, the controlling variable for how much soot is formed is not the concentration of growth species, but the surface area available for growth.

This finding led him to conclude that richer flames produce more total soot because they gen-

erate more particles in the inception stage. More incipient particles offer greater initial surface area for the incorporation of hydrocarbons.

Since the growth rate per unit area must depend on growth species concentration, this concentration must be similar from flame to flame. Dr. Harris went on to reason that there must either be enough growth species at the outset to account for the total soot growth in the richest flame, or the species must be rapidly formed within the flame from another hydrocarbon present in high enough concentration.

HE NARROWED his search to the four most abundant classes of hydrocarbons found in flames: acetylene, polyacetylenes, polycyclic aromatic hydrocarbons (PAH), and methane. Methane can be eliminated, because its concentration does not decrease as soot is produced. There is not enough PAH to account for soot formation in any flame. Neither of these two hydrocarbons can be readily formed from the other major species present. That left only acetylene and the polyacetylenes.

Acetylene contains enough hydrogen to account for the hydrogen content of soot measured in the early stages of growth. But among the polyacetylenes, only diacetylene could possibly supply enough hydrogen. That left acetylene and diacetylene.

There is more than enough acetylene to account for the mass of soot produced. There is not enough diacetylene, and while diacetylene can be formed from the abundant supply of acetylene, the reported rate of conversion is too slow for diacetylene to play a significant role. That left only acetylene.

Dr. Harris verified that acetylene is the growth species by determining that the slight increase in growth rate per unit area is proportional to the increase in acetylene concentration (see Figure 1). He also found that the rate constant he measured was in agreement with the reported rate constant for the decomposition of acetylene on carbon. These findings confirmed his hypothesis that soot particles grow in flames by the incorporation and subsequent decomposition of acetylene.

"Now that we know how soot grows," says Dr. Harris, "we can examine how it begins with greater understanding. Then, perhaps our knowledge will be complete enough to suggest better ways to reduce soot."

THE MAN BEHIND THE WORK

Dr. Stephen J. Harris is a Staff Research Chemist at the General Motors Research Laboratories. He is a member of the Physical Chemistry Department.

Dr. Harris graduated from UCLA in 1971. He received his Master's and Ph.D. degrees in physical chemistry from Harvard University. His doctoral thesis concerned Van der Waals forces between molecules. Following his Ph.D. in 1975, a Miller Institute Fellowship brought him back to the University of California, this time at Berkeley, where he spent two years studying laser-induced chemistry. He joined General Motors in 1977.

Dr. Harris conducted his investigation into soot particle growth with the aid of Senior Science Assistant Anita Weiner. His research interests at GM also include the use of laser diagnostic techniques in combustion analysis, with special emphasis on intracavity spectroscopy.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

APRIL, 1934: "Speed is the life blood of commercial aviation. The accomplishments that lie ahead for this year of 1934 are astonishing. We shall see the map of the United States so shrunken by the devouring speed of scheduled air transport that the time from New York to Los Angeles will be about 17½ hours, and in the reverse direction, with the favorable prevailing westerlies, about 15 hours. The goal of an air journey between any two points in the United States without the loss of a business day will come close to attainment. Its significance will be emphasized by a much more extended use of sleeping planes with real berths. By the time this article reaches its readers interested folk will have had an opportunity to inspect the new Douglas airliner, 41 of which, each powered with two Wright Cyclone 700-horsepower engines and equipped with Sperry automatic pilots, will make up the fleet of Transcontinental and Western Air. This transport cruises at 183 miles per hour. Full load means 14 passengers, 600 pounds of cargo and a crew of three."

"Director de Voûte of the Bosscha Observatory in Java reports on Proxima Centauri, the faint star that shares the rapid proper motion of Alpha Centauri although it is more than 10 degrees away from it. His measures give a parallax of .746 ± 0.006 degree (substantially the same as that of Alpha Centauri) and fully confirm its relation to the latter. It will take a good deal more observation to determine with certainty whether this faint object is really a little nearer than Alpha Centauri or a little farther, so that we must wait to learn whether it is the nearest of all the stars."

"A world's record for rotational speed! Considerable public interest has been aroused by a centrifuge that has been operated at a speed of 20,000 revolutions per second. This represents a maximum centrifugal force of 7,600,000 times the force of gravity and a peripheral speed of 1,390 miles per hour. It is said to be the world's fastest rotational speed for any man-made article without qualification as to type or category. The rotor of this centrifuge, designed by Dr. J. W. Beams, is of conical shape, having a maximum diameter of one centimeter. It is mounted in a cup, also of conical shape, but of slightly different angle, so that the rotor can contact the cup only at its largest diameter. The cone is grooved with a series of flutings, and apertures are provided in the cup so that compressed air or gas may be directed against these grooves at such an angle as to cause rotation."

"The repeal of Prohibition has introduced many new problems to industry, not the least of which is the predicament of the producers of grain alcohol. Every chemist knows that alcohol produced from grain is identical with the alcohol produced from molasses. However, the Government regulations covering distilleries specify that only the alcohol derived from domestic grains may be used for beverage purposes. This rule is obviously designed to alleviate the farmer's plight by giving him a new market for his grain, but it apparently closes the door on the industrial alcohol producers, most of which use 'blackstrap' molasses as a raw material."

SCIENTIFIC AMERICAN

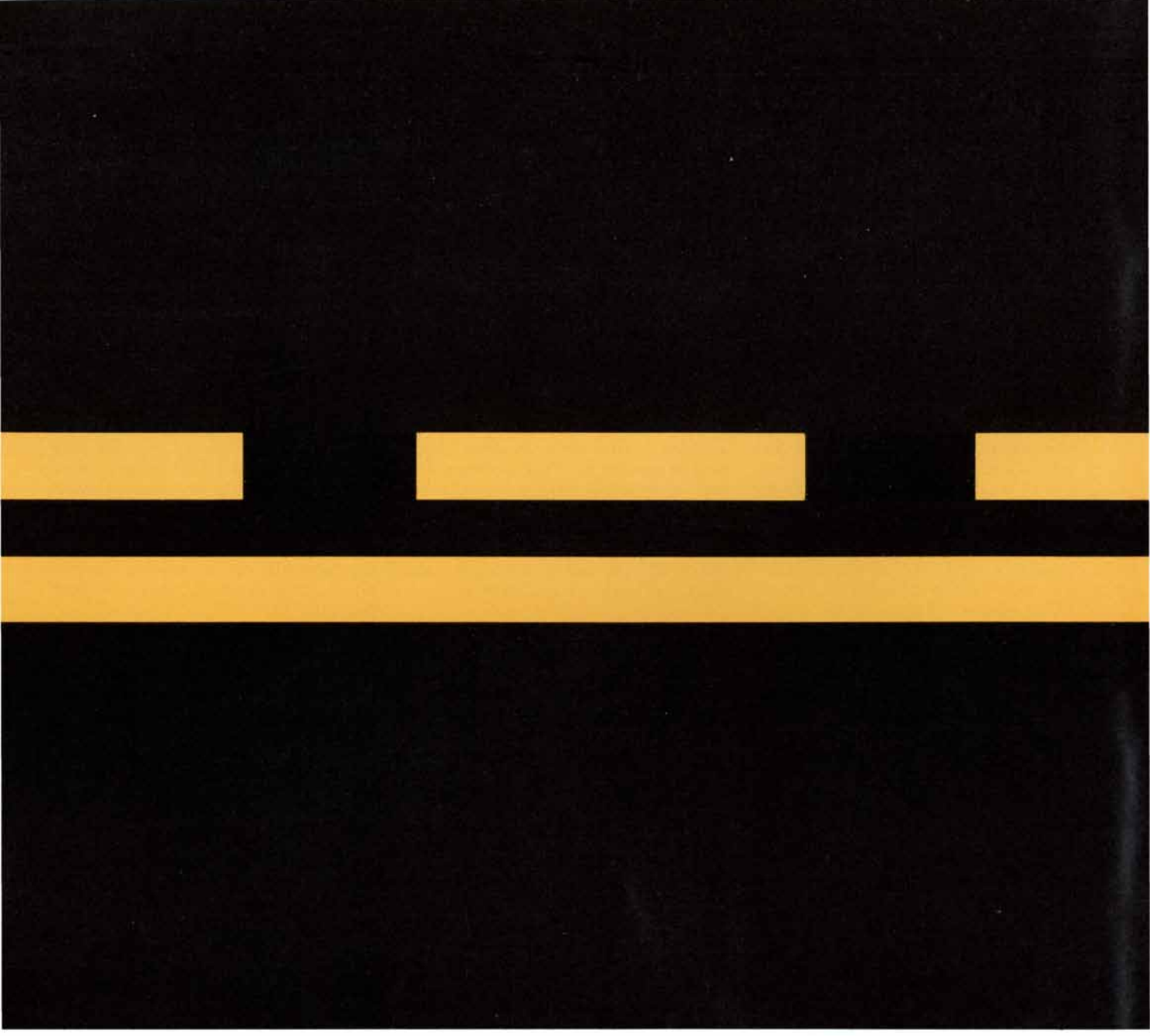
APRIL, 1884: "Dr. Stéphanne Tarnier, an able surgeon at the Maternité in Paris, probably taking his hint from the incubators that are used for hatching chickens, has devised a similar apparatus for protecting prematurely born infants from the influence of the air and allowing them to develop without accident. The infant, immediately after birth, and after the first cares have been given it, is put into the apparatus clothed like other nurslings and makes its exit therefrom only when it is sufficiently hardy and strong to live like other children in the open air. Every two or three hours it is taken out for a few minutes to be nursed at the breast or, if it is sick, to be fed upon asses' milk."

"According to the statistics of the British Board of Trade, the United States four years ago supplied 75 per cent of all the wheat and flour imports into Great Britain. In 1881 this import decreased to 69 per cent, in 1882 to 55 per cent and in 1883 to 46 per cent. In other words, the import of 93,000,000 bushels in 1881 diminished to 74,000,000 in 1883. The decrease is not due to a reduced consumption, for the total import has increased from 136,000,000 bushels in 1881 to 160,000,000 in 1883. While we thus see a constant diminution in Great Britain's imports from the United States, we find an increase from other countries, particularly Russia and India."

"Recent research in cerebral physiology has been directed toward the subject of the localization of sensory areas on the cortex of the brain, and it has been productive of many very interesting discoveries. From an analysis of 32 recorded cases with autopsies Dr. M. Allen Starr reaches the following conclusion regarding the pathology of hemianopsis (blindness in half of the visual field): that the visual area lies in the occipital lobe of the cortex, that the symptoms other than the visual cannot be referred to any lesion other than one of the occipital lobe and that the right occipital lobe receives impressions from the right half of both eyes and the left occipital lobe from the left half of both eyes."

"There is one side of preventive medicine that may be urged upon the public with a strong chance of securing their attention, and that is the expensiveness of disease. This may be estimated in several ways, and it includes a number of factors. It has been calculated by statistical hygienists that of the cases of disease now current in civilized communities, about *one-third* could have been prevented by intelligent sanitation, personal or general. Then the actual loss to these patients or their families is represented by one-third of the whole amount paid doctors, druggists, nurses, etc., in a community, plus the loss of time, whatever that may be. This is only the first item in the bill of charges. One-third of all the investment locked up in hospitals, dispensaries, asylums, homes, etc., could be put to profitable and productive use were the laws of health observed. We must also take into account the sequelae of disease in destroying ability to work, and thus casting the heavy expenses of permanent invalidism on the family or the commonwealth, or by a fatal result depriving the community of a life that would have possessed a value as capital applied to the production of wealth."

"The City of New York is provided with 33 miles of double railway tracks, built on iron posts—iron bridges, in fact—that occupy some of the finest streets and avenues. On these tracks the steam passenger trains roar and whiz along at intervals of a minute in each direction; the smoke and cinders are poured into the windows of the adjacent dwellings, in many cases only two feet from the railway; awnings are set on fire by sparks; passengers and workmen are frequently knocked off the station platforms and fall 20 feet to the pavement, to be picked up dead; tools, hot water, fire and lumps of coal drop upon the heads of luckless pedestrians or car men in the street below; and, finally, light iron shavings, cut from the wheels of the cars by the brakes, float down through the air and lodge in the eyes of passers-by. These are a few of the nuisances that New Yorkers endure for the sake of enjoying the luxury of rapid transit."



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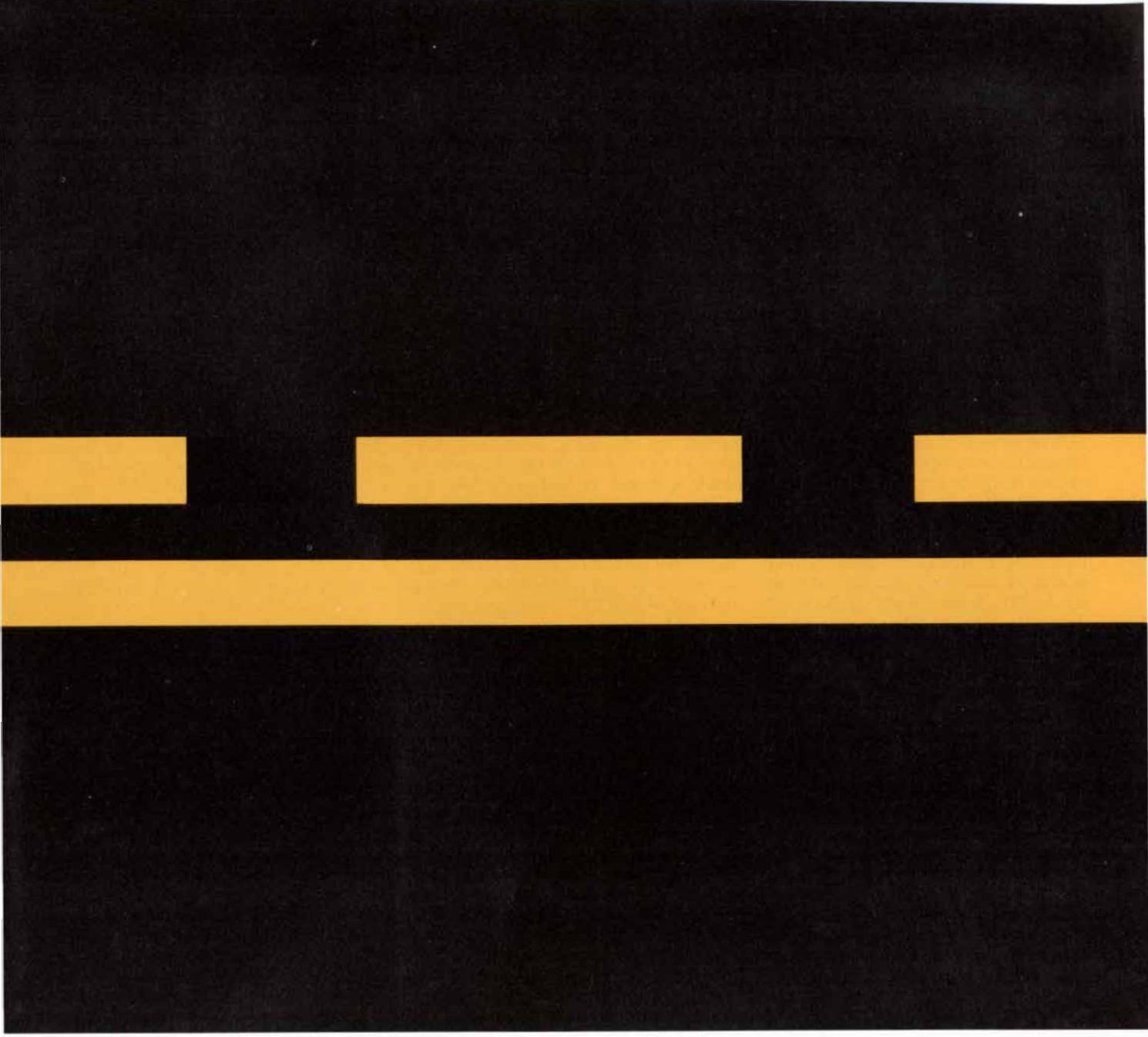

devices. But good security requires something from everyone involved with information systems.

Both the suppliers and users of computers, software and telecommunications have a responsibility to help ensure that such information systems are used conscientiously, and with the understanding that other people depend on these systems too.

Because when it comes to keeping information secure, each one of us is in the driver's seat. IBM®

THE AUTHORS

R. V. SHORT ("Breast Feeding") holds an endowed chair in reproductive biology in the departments of anatomy and physiology at Monash University in Australia. He qualified as a veterinarian at the University of Bristol in England in 1954 before coming to the U.S. to continue his studies. He obtained his M.S. in genetics at the University of Wisconsin in 1955 and then returned to England. He has two degrees from the University of Cambridge: his Ph.D. in reproductive biology (1958) and his Sc.D. in the same subject (1969). He was also Reader in reproductive biology at Cambridge. Soon after completing his second degree at Cambridge he became director of the unit of reproductive biology at the Medical Research Council in Edinburgh. After serving in that job for 10 years he moved to Monash. In addition to his post at Monash he is chairman of Family Health International at Research Triangle Park in Chapel Hill, N.C. Short's main research interests are the comparative aspects of reproduction in mammals and contraceptive research and development.

NICK SCOVILLE and JUDITH S. YOUNG ("Molecular Clouds, Star Formation and Galactic Structure") are astronomers who have done much work on the subject of their article at radio wavelengths. Scoville is professor of astronomy at the California Institute of Technology. He earned his Ph.D. in astronomy from Columbia University, then did postdoctoral work at the University of Minnesota and at Cal Tech. From 1975 to 1983 he was professor of astronomy at the University of Massachusetts at Amherst, a job he left to take up his current one. His scientific work has included probing the structure of the galaxy by means of carbon monoxide emissions and detailed studies of regions of star formation such as the Orion nebula. Scoville writes: "My consistent pleasure in this work has been to follow the process of deduction from the very limited astronomical observations; the one rule learned from such experience is that invariably our predictions are shortsighted compared with astronomical reality." Young is a member of the department of physics and astronomy at the University of Massachusetts. Her B.A. in astronomy is from Harvard University and her Ph.D. in physics is from the University of Minnesota. Scoville is the son of Herbert Scoville, Jr., who has written three articles for SCIENTIFIC AMERICAN on arms and arms control. Young is the daughter of Vera C. Rubin, who has written two articles for the magazine: "The Dynamics of the Andromeda Nebula" (June, 1973) and "Dark Matter in Spiral Galaxies" (June, 1983).

A. JAYARAMAN ("The Diamond-Anvil High-Pressure Cell") is a member of the technical staff of the AT&T Bell Laboratories. Born in India, he went to the University of Madras as an undergraduate, getting a B.S. in 1946. In 1950 he moved to the Raman Research Institute in Bangalore to work with the physicist C. V. Raman on optical phenomena in solids. He remained at the Raman Institute until 1960, earning his M.S. (1954) and his Ph.D. (1960) from Madras along the way. In 1960 he came to the U.S. to join the staff of the Institute of Geophysics at the University of California at Los Angeles. It was there that he became interested in the physics and chemistry of solids at high pressure. It is an interest he has pursued since joining the staff of Bell Laboratories in 1963.

JOHN T. SNOW ("The Tornado") is assistant professor of geosciences at Purdue University. He was graduated from the Rose-Hulman Institute of Technology (then called the Rose Polytechnic Institute) in 1968 with a B.S. and went on to get his M.S. in electrical engineering there in 1969. After obtaining his master's degree he entered the army, in which he served mainly as a meteorologist in the Signal Corps. He left the army to pursue his studies at Purdue, which awarded his Ph.D. in atmospheric science in 1977. Snow writes: "I have professional interests in the dynamics of swirling flows, severe thunderstorms, mesoscale forecasting and meteorological observations. Most of my current efforts are directed at unraveling the physics of intense columnar vortexes such as the tornado."

TOMASO POGGIO ("Vision by Man and Machine") is associate professor in the department of psychology and the Artificial Intelligence Laboratory at the Massachusetts Institute of Technology. He writes: "After completing my Ph.D. in theoretical physics at the University of Genoa I went to the Max Planck Institute for Biological Cybernetics in Tübingen to work with Werner Reichardt on the amazingly smart and small visual system of the fly. In 1976 I began collaborating with the late David Marr of M.I.T. on the computational approach to vision. At the same time I undertook a complementary kind of work: trying to understand the information-processing mechanism of the brain and its basis in the biophysical properties of nerve cells. In 1981 I moved to M.I.T. to continue work on computational problems in vision and their applications to robotics and biological information processing."

GERALD M. EDELMAN ("Cell-Adhesion Molecules: A Molecular Basis for Animal Form") is Vincent Astor Professor at Rockefeller University. He was graduated from Ursinus College with a B.S. in 1950 and went on to earn his M.D. from the University of Pennsylvania School of Medicine in 1954. After a year as a medical house officer at the Massachusetts General Hospital and two years as a captain in the U.S. Army Medical Corps he entered Rockefeller (then known as the Rockefeller Institute for Medical Research) to begin work on his doctorate. His doctoral research was on the structure of gamma globulin, a protein that has a crucial role in immunological responses. After getting his Ph.D. in 1960 he stayed at Rockefeller and continued the work. By 1969 he had described the amino acid sequence and internal-subunit structure of gamma globulin, a task for which he was awarded the Nobel prize for medicine or physiology in 1972. Edelman is head of the laboratory of developmental and molecular biology at Rockefeller and also director of the Neurosciences Institute on the Rockefeller campus.

JOHN R. HORNER ("The Nesting Behavior of Dinosaurs") is curator of paleontology at the Museum of the Rockies and adjunct assistant professor of geology at Montana State University at Bozeman. He went to the University of Montana in Missoula as an undergraduate. In 1976 he became research assistant in the department of geological and geophysical sciences at Princeton University and assistant curator of the Museum of Natural History there. In 1982 he took up his current jobs. Horner writes: "My interests are somewhat one-sided, as nearly all my time is devoted to dinosaur research. I am interested not only in their behavioral biology but also in their morphology, physiology, ontogeny and evolution. If I had not been lucky enough to get a job working on dinosaurs, I would have continued my study of them as a hobby."

C. F. W. HIGHAM ("Prehistoric Rice Cultivation in Southeast Asia") is professor of anthropology at the University of Otago in New Zealand. He was born and educated in England, earning two degrees from the University of Cambridge. His undergraduate studies were in archaeology and anthropology. He got his B.A. in 1962. His Ph.D. in anthropology was awarded in 1966. Most of his work has been on the prehistory of Southeast Asia, in particular that of Thailand. Higham's nonprofessional interests include sailing, boat building and house building; he built both his sailboat and his house.

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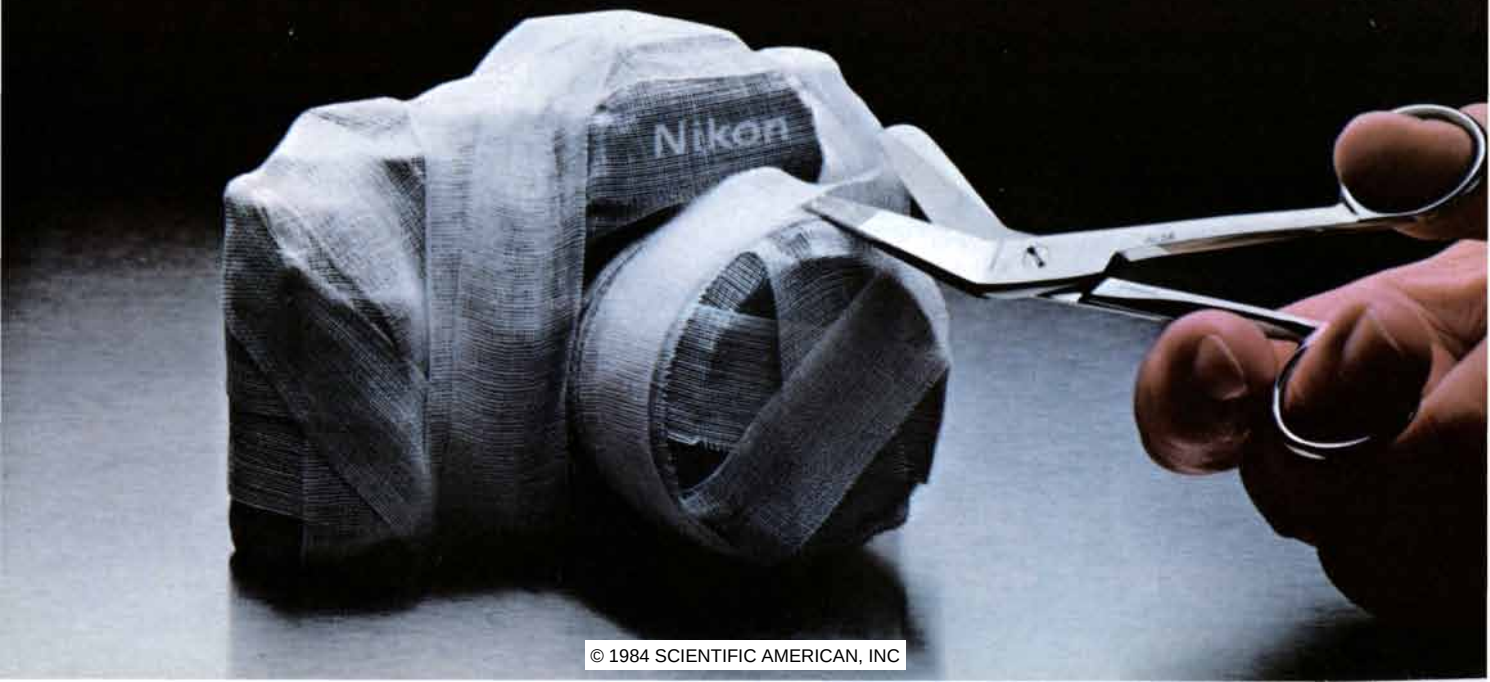

High contrast. Shot in Aperture-Priority with the Nikon FA.

Back light. Shot in Programmed with the Nikon FA.

Available light. Shot in Programmed with the Nikon FA.

Sun-in-frame. Shot in Shutter-Priority with the Nikon FA.

Shot in Aperture-Priority with a leading multi-mode SLR camera.

Shot in Programmed with a leading programmed SLR camera.

Shot in Programmed with the biggest selling SLR camera.

Shot in Shutter-Priority with a competitor's "top-of-the-line" SLR camera.

The pictures you see here are actual unretouched photographs, shot simultaneously without any exposure compensation. ©Nikon Inc. 1984.

The Nikon FA. The biggest advance in automatic photography since automatic exposure.

Until now, the metering system of any automatic camera could do just one thing. Measure light and give you a technically correct exposure.

But as any photographer knows, a technically correct exposure doesn't always give you the best picture.

That's why Nikon developed the FA. The first camera with AMP (Automatic Multi-Pattern) metering.

AMP is the only metering system that can automatically give you optimum exposure, not just technically correct exposure, even under extreme lighting conditions.

So what you see in your pictures is a lot more like what you saw with your eyes.

How AMP works.

AMP metering divides your picture into five segments and then individually measures and compares each segment, evaluating such factors as contrast ratios, variations in brightness levels and percentages of light and dark areas.

It then processes this information in its own Nikon microcomputer, comparing the components of your picture with those of nearly 100,000 photographs programmed into its memory, and instantly chooses the optimum exposure.

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The FA gives you more choices than any other camera.

Shoot in the Dual-Program mode and the camera does it all for you. With one program for normal and wide-angle lenses and a high-speed program for Nikon AI-S and Series E lenses, 135mm and longer.

Or switch to Shutter-Priority.

With the FA's top shutter speed of 1/4000 of a second, there's not much you can't catch.

If you're most concerned about controlling the sharpness of foreground and background, Aperture-Priority is at your command.

And of course, you can also take full creative control in Manual.

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Use a Nikon motor drive and shoot up to 3.2 frames-per-second.

Or attach a variety of Nikon Speedlights to activate the FA's automatic TTL (through-the-lens) flash metering system, and shoot flash pictures at sync-speeds up to 1/250 of a second.

The FA is also compatible with all current and many older Nikon lenses, and a full range of Nikon accessories.

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COMPUTER RECREATIONS

How to handle numbers with thousands of digits, and why one might want to

by Fred Gruenberger

EDITOR'S NOTE: The author of "Computer Recreations" this month, Fred Gruenberger, is professor of computer science at California State University at Northridge. Gruenberger's acquaintance with computing machinery began more than 40 years ago; he has since published 28 books on computing, and from 1973 to 1981 he edited the monthly magazine *Popular Computing.*

Beginning next month the "Computer Recreations" department will be conducted by A. K. Dewdney, associate professor of computer science at the University of Western Ontario. Dewdney's chief professional interests are in discrete mathematics and the theory of computation, but he is known to many readers for his investigations of two-dimensional science and technology, described in this space by Martin Gardner (see "Mathematical Games"; SCIENTIFIC AMERICAN, July, 1980). Dewdney's elaboration of this work (*The Planiverse: Computer Contact with a Two-dimensional World*) was recently published by Poseidon Press, and a collection of his essays on topics in computer science, *The Turing Omnibus,* will be published next year by Computer Science Press.

If you have a calculator with a key for squaring a number, try this: enter the number 1.0000001 and press the square key 27 times. The procedure is equivalent to raising the initial number to the 134,217,728th power. The correct result, accurate to 10 significant digits, is 674,530.4707, but the calculator will almost surely give a different answer. The problem is designed to reveal the precision level of the machine. The table on page 24 gives the results obtained with several calculators and with versions of the BASIC and Fortran programming languages running on a few computers. None of the machines gets even seven digits correct.

With most electronic calculators the operation of squaring is not equivalent to entering a number and multiplying it by itself. In the latter operation the factors that enter into the multiplication are limited in their size or precision by the number of digits the machine can display. Squaring, on the other hand, operates on the representation of a number stored in the machine, which generally includes a few "guard digits," that is, extra digits that enter into each calculation but are hidden from the operator. Thus if you calculate the square root of 2 on a machine with an eight-digit display and two guard digits, the result will be shown as 1.4142136 but stored internally as 1.414213562. Pressing the square key should recover the original value 2.0000000, whereas multiplying 1.4142136 by itself gives an answer of 2.000000106.

In most calculations an error in the seventh decimal place is of little consequence. Suppose, however, the calculation is made in a computer program that will execute one sequence of instructions if the value is exactly 2 but a different sequence otherwise; the effect of any inaccuracy could be catastrophic. The safest way of avoiding this hazard is probably to round the calculated value to a known level of precision before testing it for equality with 2. In other circumstances the stratagem of rounding offers no help. In the problem of repeatedly squaring a decimal fraction the only way to improve the quality of the result is to maintain greater accuracy throughout all stages of the calculation.

For most numerical work a precision level of eight or nine digits is ample. It should suffice for balancing a checkbook provided the amounts involved are no greater than $1 million or so. No constant of nature is known with a precision of more than 12 significant digits. Achieving even moderate precision in the final result, however, may call for much higher precision in the course of the calculation. When 1.0000001 is squared 27 times, getting 10 digits correct requires that all calculations along the way be accurate to 15 places.

An example of a calculation in which the need for high precision is absolute is the continuing search for larger prime numbers. For many years, before the development of the electronic digital computer, the largest number known to be prime was $2^{127} - 1$, which has 39 digits in decimal notation. With the aid of the computer, starting in 1952, the record has been broken 16 times; currently it is a number ($2^{132049} - 1$) of 39,751 digits. In testing for primality (that is, in determining whether a number can be divided by any numbers other than 1 and itself) all arithmetic must be exact.

NUMBER OF SQUARINGS	POWER	EIGHT-DIGIT PRECISION	15-DIGIT PRECISION
0	1	1.0000001	1.00000010000000
1	2	1.0000002	1.00000020000001
2	4	1.0000004	1.00000040000006
3	8	1.0000008	1.00000080000028
4	16	1.0000016	1.00000160000120
5	32	1.0000032	1.00000320000496
6	64	1.0000064	1.00000640002016
7	128	1.0000128	1.00001280008128
8	256	1.0000256	1.00002560032640
9	512	1.0000512	1.00005120130818
10	1024	1.0001024	1.00010240523794
11	2048	1.0002048	1.00020482096271
12	4096	1.0004096	1.00040968387705
13	8192	1.0008192	1.00081953559497
14	16384	1.0016391	1.00163974282853
15	32768	1.0032809	1.00328217441361
16	65536	1.0065726	1.00657512149610
17	131072	1.0131884	1.01319347521490
18	262144	1.0265507	1.02656101821804
19	524288	1.0538063	1.05382752412486
20	1048576	1.1105077	1.11055245060312
21	2097152	1.2332274	1.23332674554061
22	4194304	1.5208498	1.52109486126578
23	8388608	2.3129841	2.31372957696917
24	16777216	5.3498954	5.35334455534193
25	33554432	28.621381	28.6582979282091
26	67108864	819.18345	821.298040141993
27	134217728	671061.52	674530.470741078

Result of squaring 1.0000001 repeatedly with limited precision

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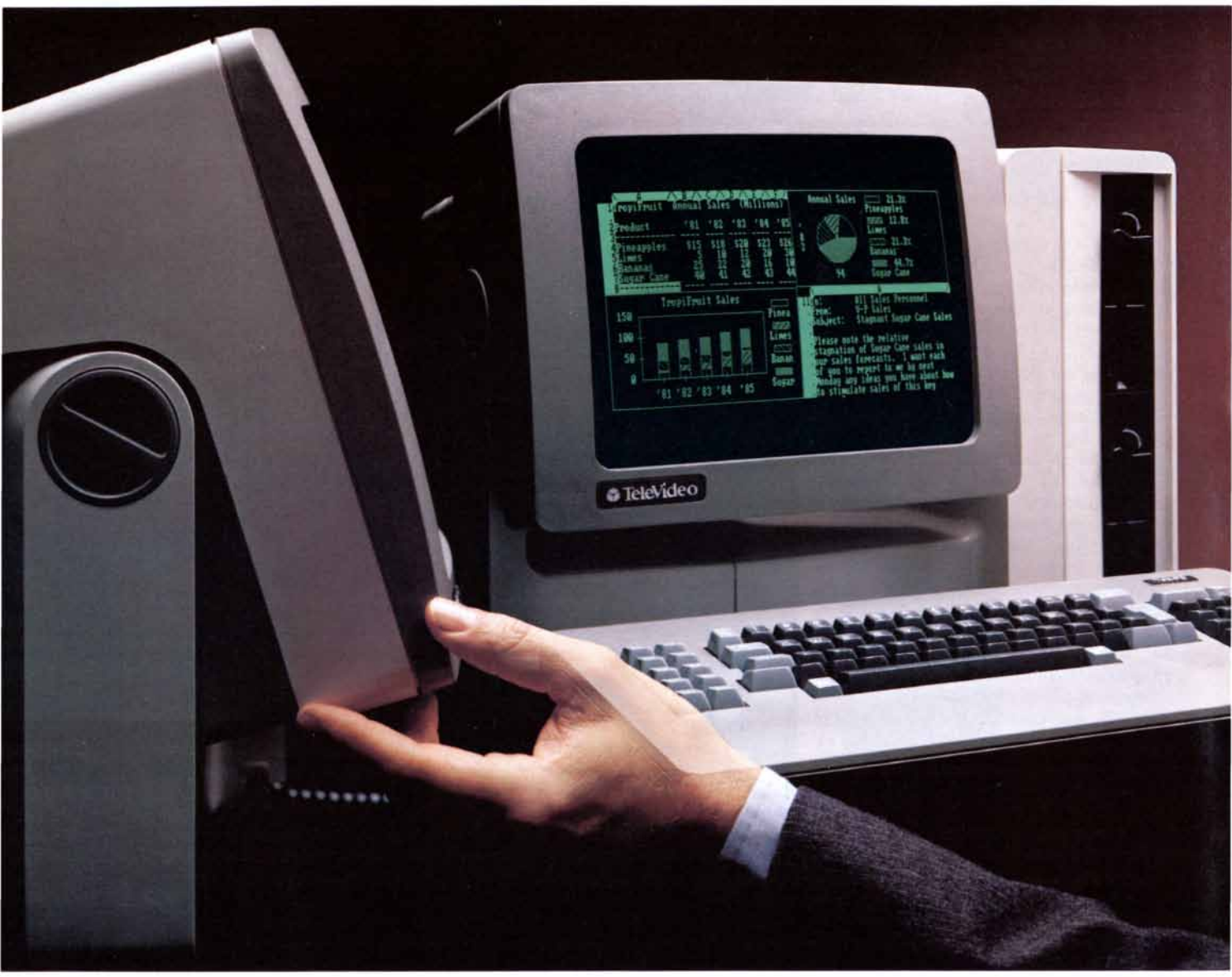

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Monitor	YES	OPTIONAL	YES	OPTIONAL
Screen Size	14"	12"	14"	12"
Tilt Screen	YES	NO	YES	NO
Quiet Operation	YES (NO FAN)	NO	YES	NO
Memory	128K	128K OPTION	256K	256K OPTION
Graphics Display (640 x 200 resolution)	YES	OPTIONAL	YES	OPTIONAL
Printer Port	YES	OPTIONAL	YES	OPTIONAL
Communication Port	YES	OPTIONAL	YES	YES
MS™-DOS/BASIC®	YES	OPTIONAL	YES	OPTIONAL
System Expansion Slot	YES	YES	YES	YES
RGB and Video Port	YES	OPTIONAL	YES	OPTIONAL
Typical System Price	**$2995**	**$3843**	**$4995**	**$5754**

compatibles. the best software.

and has the standard—not optional—features you need to take full advantage of every job your software can do.

Study the chart at the left. It proves that TeleVideo—not IBM—offers the best hardware for the best price.

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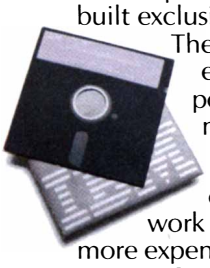
2nd Disk Drive	YES	OPTIONAL
Quiet Operation (No Fan)	YES	NO
Ergonomic Display	YES	NO
Communication Port	YES	OPTIONAL
International Power Supply	YES	NO
MS™-DOS 2.11	YES	NO
Graphics Display	YES	YES
Typical System Price	**$2995**	**$3710**

THE BEST MICROCHIPS.

What is perhaps most impressive about the TeleVideo IBM PC Compatible can be found deep within its circuitry. We use the same 8088 central processing unit that runs an IBM PC. But we also employ new VLSI (Very Large Scale Integration) microchips that are designed and built exclusively for TeleVideo. These interface more efficiently with the powerful 8088 and yield numerous benefits.



For example, our tiny custom chips do the work of many of the larger, more expensive circuit boards in an IBM PC. So we can offer a computer system that comes in one attractive, integrated case, is ready to run and occupies less desk space. A computer that edges out IBM's added-cost component system for reliability, ease of service and purchase simplicity.

Fewer circuit boards to cool also allowed us to eliminate the noisy, irritating fan IBM and most other PCs force you to put up with. And TeleVideo compatibles accept any IBM hardware options without modification.

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But the Tele-PC is only one element of the TeleVideo IBM PC Compatible line.

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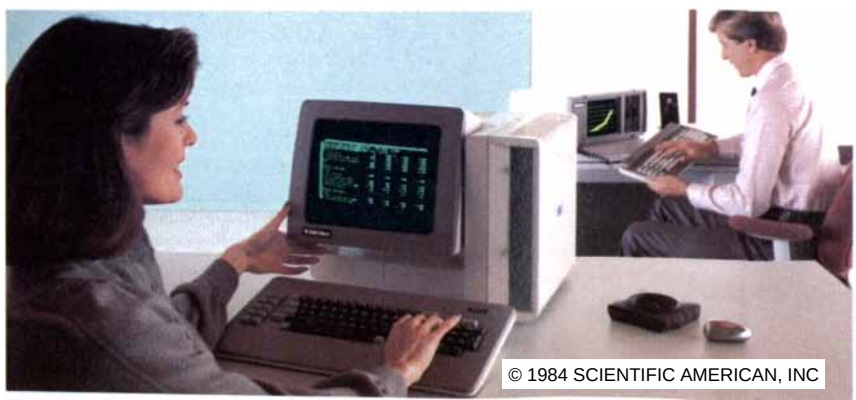
Before you invest, make a few simple comparisons. You'll find that TeleVideo—not IBM or COMPAQ—has the best hardware for the best software. At the best price.



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Computing the value of pi is another problem of long standing that calls for very high precision. The record was held for many years by the British mathematician William Shanks; working by hand, he calculated 528 correct digits (and another 179 incorrect ones). Pi is now known to 8,388,608 digits.

Given that the mechanization of high-precision arithmetic began more than 30 years ago and that computing power has been getting cheaper and becoming more widely available ever since, one might expect the list of known results to be quite extensive. Actually the list of known high-precision numbers is remarkably short:

The square root of 2 is known to one million decimal places, and the cube root of 16 is known to 1,000 places.

The real root of Wallis' equation, $X^3 - 2X - 5 = 0$, is known to 4,000 digits. (The equation is one chosen by the 17th-century British savant John Wallis for an illustration of Newton's method for the numerical solution of equations; it has served since as a test of many other methods of approximation.)

Harry L. Nelson of the Lawrence Livermore National Laboratory (who once held the record with David Slowinski of the same institution for the largest known prime number) has calculated the factorial of one million, namely the product $1{,}000{,}000 \times 999{,}999 \times \ldots \times 2 \times 1$. The result has 5,565,709 digits and fills a stack of standard printout paper five inches high.

A problem known as the 196 problem has been carried through 50,000 stages of calculation, at which point the numbers being dealt with are 21,000 digits long. Another tantalizing problem, the $3N+1$ problem, has been investigated for isolated values with as many as 1,000 digits. Both problems are discussed in more detail below.

The Fibonacci sequence (1, 1, 2, 3, 5, 8, 13, 21 . . . , in which each term is the sum of the two preceding terms) has been calculated explicitly for the first 10,000 terms. At the 10,000th term the numbers have more than 2,000 digits.

Euler's number, *e*, the base of the natural logarithms, has been calculated to more than 125,000 decimal places.

A few other isolated results might be cited. For example, R. William Gosper of Symbolics, Inc., employing a method based on the manipulation of continued fractions, has calculated 2,800 digits of the seventh root of 306. (The root has no special significance; the task was selected at random as a test of the method.)

Most of the problems listed above are of the kind in which the need for high precision is intrinsic; they are challenging just because they call for keeping track of more digits than most people can imagine ever needing. A high-precision problem that is commoner and more practical, and less artificial, comes up in solving for the roots of a quadratic equation (an equation that has the form $AX^2 + BX + C = 0$). The quantity $B^2 - 4AC$, called the discriminant of the equation, determines whether the roots are real or imaginary. If the discriminant is positive, the roots are real; if it is negative, they are imaginary; if $B^2 - 4AC$ is exactly zero, the equation has two equal roots. Hence even a small error in the evaluation of the discriminant can make a qualitative difference in the solution of the equation.

A similar sensitivity to small numerical errors can develop in solving a system of simultaneous linear equations. Consider the system

$$\begin{aligned} 53.17X - 18.91Y - 5.67Z &= -174.65 \\ -12.65X + 36.16Y - 47.08Z &= 298.59 \\ 303.80X - 203.03Y + 112.89Z &= -1769.02 \end{aligned}$$

The system was constructed so that the three equations are satisfied by the values $X = -3$, $Y = 2$ and $Z = -4$, but those values do not represent a unique solution. Indeed, although it is not apparent from mere inspection, there can be no unique solution because two of the equations describe planes that are parallel to each other. (The third equation of the set is equal to five times the first equation minus three times the second equation and so contributes no independent information.)

The impossibility of solving the equations can be discovered by calculating the quantity called the determinant of the matrix of coefficients. The determinant of a matrix is evaluated by forming all possible combinations of elements that are in neither the same column nor the same row; the elements in each combination are multiplied, then the products are summed. If the determinant is found to be zero, the system of equations has no solution and one knows to proceed no further (or, more important, one can arrange to have a computer program halt at this point). Here, however, a calculation of the determinant based on the scheme called basket weaving and using arithmetic accurate to nine digits gives an answer not of zero but of −.000202179. Other methods of evaluation may yield a correct result in this example but not in others; the point is, with nine-digit precision the result cannot be relied on. Moreover, the system of equations given here is a small one, with coefficients having no more than five significant digits; when the system is larger, the problem becomes acute.

Many problems in number theory and other branches of mathematics require extreme precision for the representation of very large integers. The 196 problem is an example. To work the problem start with any positive integer of two digits or more. Reverse the digits and add the reversed number to the original one. Now reverse the sum and add again, and continue the process until the result is a palindromic num-

1.0000001

1.00000020000001

1.0000004000000600000040000001

1.00000080000028000005600000700000056000002800000080000001

1.000001600001200000560000182000043680008008001144000128700011440000800800
043680001820000056000001200000016000000 1

1.000003200004960004960003596002013760906192336585705183028048806451225290
245025792874737364714356565722780108044657227671435634737362257928529024 48
645122428048801051830033658560906192020137600359600004960000049600000320 00
0001

1.000006400020160041664063537676245194974430121663461681220599659328917561
102456016742359779559107208715427501663354524863006088759570934516112681 99
153831856914237352901072595710907723235985870855649116615937335679742011 61
434343572772188085733555689437511105995105806963778061809682674493540378 03
990834546389685791612895510241362153031480464829012725019140645477741557 96
971321757005849546165430121619949743687624512063537600416640002016000006 40
000001

1.000012800081280341377066802645669423620652593817045586724716639752509356
370660496688786863233980858666587877408486616928888599507374476547533451 68
002963740073746995710556007241670099300929440107854408072554911252317789 92
849980801309396592757494113324438154763359844908980286908211809446877601 78
266511869228209004751039990940280045411637406975397338884283676755932544 23
047914478918135752102429288143361653459171040814216776401746346343970859 72
839009540706607815241562535966383451324140370946893647800306536699175793 20
392634955460025784209902391880928345490689625104448618589291193750025424 34
572320889769109362436235325985158624722403373962502148033363010732930713 92
408811775715101210696782628924296789851669470330413575989281861372471283 44
637482304783585492600325645400029538693329144544905822301135624937328904 58
571501560870702174970266185257957423611226456640106680000341376000812800 00
1280000001

Exact results for a few squarings of 1.0000001

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CALCULATOR	RESULT	PERCENT ERROR
Texas Instruments SR-52	674520.6053	.00146
Hewlett-Packard 33, 67, 41C	674494.0561	.00540
Sharp Electronics EL506	674492.75	.00559
Monroe Calculator 1930	674383.1672	.02183
Texas Instruments 30	674363.69	.02473
COMPUTER AND LANGUAGE		
Double-precision Fortran (CDC Cyber)	674530.5363	.00000973
Eight-digit Fortran (CDC Cyber)	674530.5765	.00001568
Apple II BASIC	22723.9709	96.63114
IBM Personal Computer BASIC	8850273.	1212 06423
Ontel BASIC	8886690.	1217.46401

Accuracy of some machines and programming languages in repeated squaring

ber: one that reads the same forward and backward [*see illustration below*]. For most starting numbers a palindrome is reached very quickly; the series beginning with 195, for example, ends after just four steps. The smallest number that seems never to become palindromic by this process is 196; as noted above, it has been tested through 50,000 steps. Among the first 100,000 integers there are 5,996 that apparently do not generate a palindrome no matter how long the procedure is continued (although this conjecture has not been confirmed).

The $3N+1$ problem was discussed here in January. Start with any positive integer N; if N is odd, replace it with $3N+1$; if N is even, replace it with $N/2$. Continue until N is equal to 1. For example, when the starting value of N is 9, the process yields 20 terms: 9, 28, 14, 7, 22, 11, 34, 17, 52, 26, 13, 40, 20, 10, 5, 16, 8, 4, 2 and 1. This simple procedure leads to many mysteries. Does the sequence always terminate at 1, no matter what starting value of N is chosen? Is there any pattern to the number of steps required, that is, can a formula based on the value of N predict the number of steps required? For any chosen number of steps is there invariably an odd value of N that generates a sequence of that length? (An even value of N with any specified path length can readily be found: it is 2 raised to a power of 1 less than the path length.)

193	194	195	196	197	198	199	200
391	491	591	691	791	891	991	002
1124	685	786	887	988	1089	1190	202
4211	586	687	788	889	9801	0911	
5335	1271	1473	1675	1877	10890	2101	
	1721	3741	5761	7781	09801	1012	
	2992	5214	7436	9658	20691	3113	
		4125	6347	8569	19602		
		9339	13783	18227	40293		
			38731	72281	39204		
			52514	90508	79497		
			41525	80509			
			94309	171017			
			90349	710171			
			187088	881188			
			880781				
			1067869				
			9687601				
			10755470				
			07455701				
			18211171				
			17111281				
			35322452				
			25422353				
			60744805				
			50844706				
			111589511				
			⋮				

Evaluation of the 196 problem for a few starting values

In 1980 I proposed that the average number of terms to convergence in the $3N+1$ problem is approximated by $24.64D-101$, where D is the number of digits in the starting value of N. The estimate was based on calculations made with numbers of up to about 200 digits, which I then thought were quite large. With a program for high-precision arithmetic I have been able to check the conjecture for a few larger values. For a 1,000-digit number the formula predicts convergence in 25,539 steps. I found that when N is equal to the number $1\ldots(998\text{ zeros})\ldots1$, or $10^{1000}+1$, the series descends to 1 in 23,069 steps. The number $55\ldots(997\text{ zeros})\ldots1$ yields a series with 24,413 terms. Hence on this preliminary evidence it appears the average rate of convergence is stable and predictable.

Another phenomenon first observed with small values of N that seems to persist with larger ones is a tendency for many consecutive values of N to generate series of the same length. Indeed, such strings apparently become more prevalent as N increases. For example, the 230 consecutive integers beginning with

912345678912345678900-
00000000000000000000001

all generate series with 997 terms. (Note that the prediction of the empirical formula for this number is 959 terms.)

The arithmetic operations that can be carried out directly by the central-processing unit of a typical microcomputer offer only very limited precision. In many machines the only operations provided for explicitly are addition and subtraction of integers whose length is no more than 16 bits, or binary digits; in decimal notation the largest number that can be represented is 65,536, so that the level of precision is less than five decimal digits. Even with the most powerful computers precision of more than a few dozen digits can be attained only by means of a program that combines many elementary operations to break a large number down into smaller pieces.

The flow charts on page 26 outline an algorithm for a specific high-precision calculation: the evaluation of the largest known prime number, $2^{132049}-1$. The procedure was created with a particular microprocessor in mind, namely the 6502, manufactured by MOS Technology, which is found in computers made by Apple Computer Inc., Commodore Business Machines, Inc., and other manufacturers. It would be easy to adapt the algorithm to other microprocessors.

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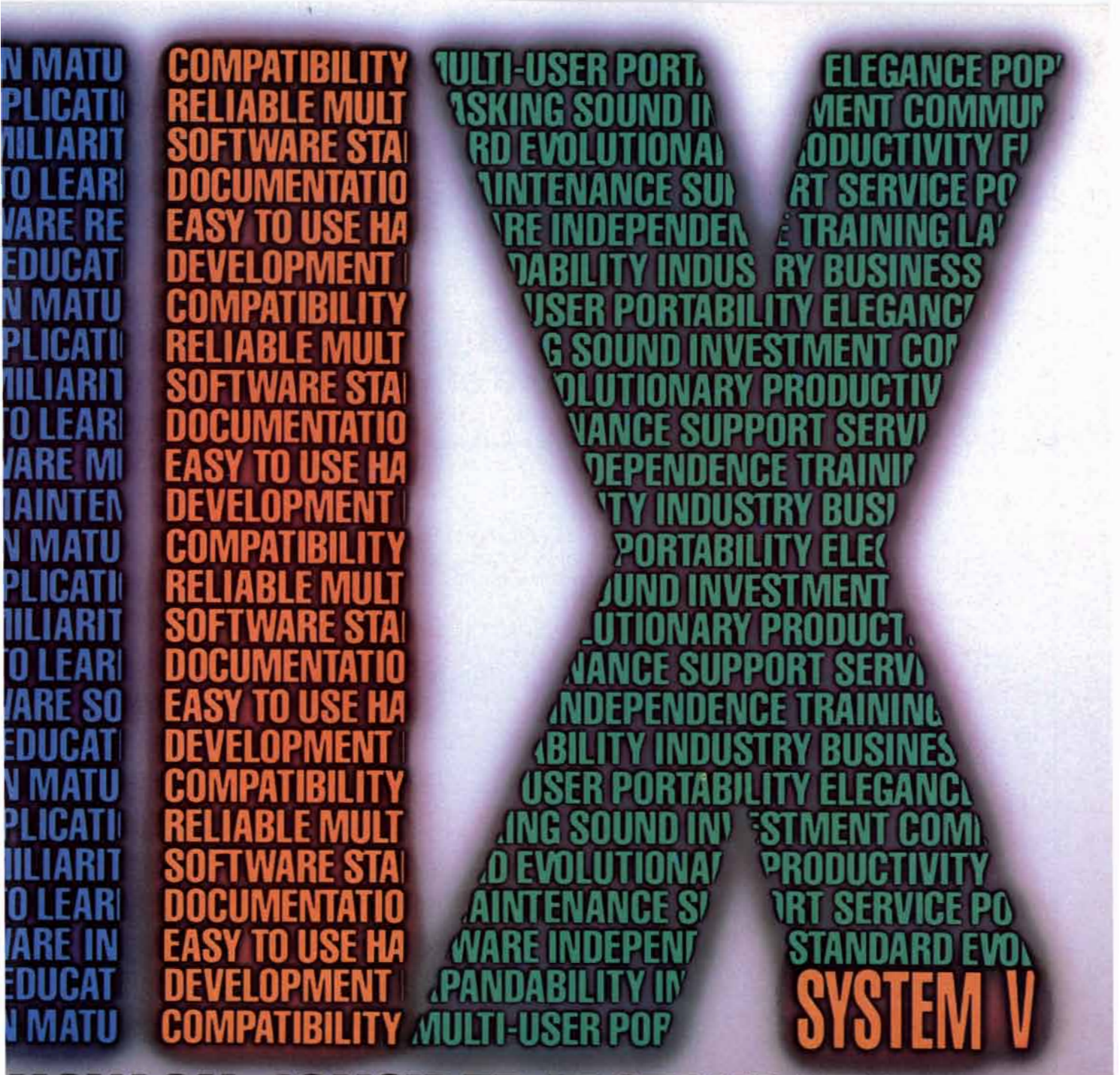

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sion in designing such a program is the choice of how a number is to be represented in the computer's memory. The processor can operate only on binary values, but one would obviously prefer to have the result of the calculation displayed in decimal form. A useful compromise is the scheme called binary-coded decimal, in which each decimal digit is separately represented by its equivalent binary value. The 6502 organizes the memory of a computer in "bytes," or units of eight bits, and so it is convenient to store a number one decimal digit to a byte. (This is not the most efficient method, but it is the simplest.)

The first step in the algorithm is to clear an area in memory 39,760 bytes long by setting each byte equal to zero. Next a starting value of 1 is put into the cleared work space, so that the area holds 39,759 zeros followed by a single 1. A counter that will be needed to keep track of the progress of the calculation is given an initial value of zero.

The main section of the program is a loop that repeatedly calls a subroutine whose function is to double the number stored in the work space. After each doubling the counter is incremented by 1 and the value in the counter is compared with 132,049. If that limit has not yet been reached, the doubling subroutine is called again; when the limit is reached, the program exits from the loop. Finally, 1 is subtracted from the value in the work space and the result is displayed.

In the flow chart at the left the doubling subroutine is marked with color; the instructions making up the subroutine are shown in the flow chart at the right. Each time the routine is called, an index (X) is set to the lowest address in the work space, where the rightmost, or least significant, digit of the number is stored. The value stored at that address is then doubled by adding it to itself. As in doing addition by hand, most of the complication arises from the need to deal with a "carry" from one digit to the next as the addition proceeds. If an earlier addition has generated a carry digit, it must be added to the new result. That result in turn must be checked for a carry digit: if the sum is greater than 9, it must be adjusted by subtracting 10, and the carry digit must be set equal to 1. The process is repeated for all 39,760 bytes of the work space.

The 6502 processor of the Apple II computer operates at a speed of more than 250,000 instructions per second. Nevertheless, the scheme shown in the flow charts would require 120 hours to compute the 132,049th power of 2. Simple short cuts could greatly reduce the running time. For example, it is not necessary to double all the digits of the work space during the early stages of the calculation, when all but a few of them are zeros. The work space might begin with a length of, say, 150 bytes and be augmented by three bytes for every 10 powers. This strategy would in itself require the execution of some additional instructions, but the overall effect would be an increase in speed.

All the numbers in the calculation of $2^{132049} - 1$ are integers, but many problems are best approached by expressing quantities in scientific notation, where a number consists of a decimal fraction called the mantissa and an exponent that gives the magnitude, or power of 10. For example, in the number representing the current year the mantissa is 1.984 and the exponent is $+3$, and the complete number is written as 1.984×10^3. A high-precision program for manipulating such numbers is necessarily more complicated than one that deals only with integers because each number has several parts (including not only the mantissa and the exponent but also their signs).

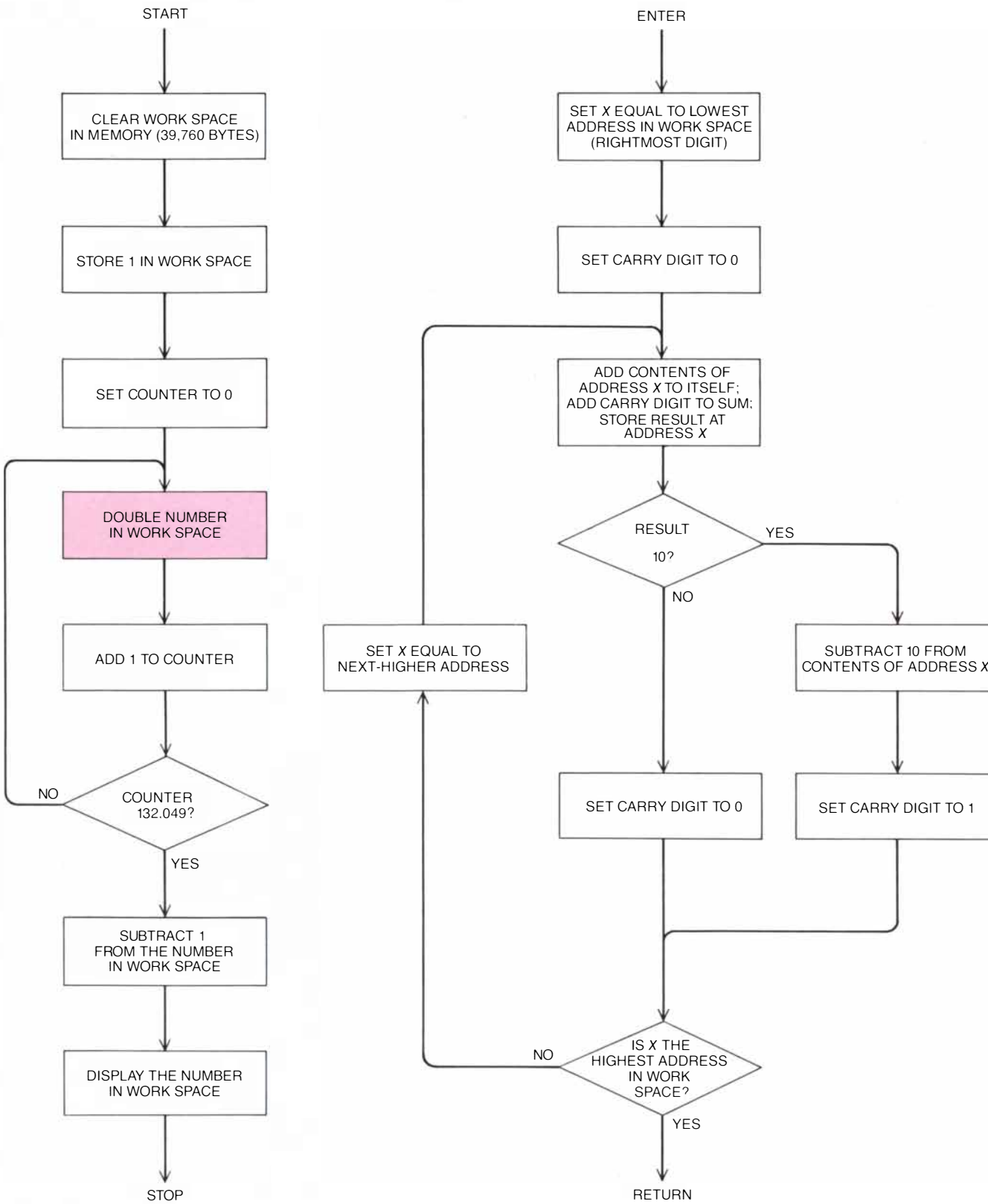
Most higher-level programming languages incorporate some facilities for calculating in scientific notation; the system is often called floating-point arithmetic. Numbers smaller than a certain size are displayed as an ordinary decimal fraction, but the values are stored internally as a mantissa and an exponent. The space allocated to the various elements of the number determines the precision and the range of values that can be represented. Giving more room to the mantissa improves the precision; a larger exponent affords a greater range. The version of BASIC incorporated into the Apple II has a fixed precision level of about nine digits.

For appreciably greater accuracy it is again necessary to resort to a software solution. Herman P. Robinson, formerly of Lawrence Livermore, has written a package of high-precision scientific-notation programs in the machine language of the 6502 microprocessor. The programs can operate at any level of precision up to 600 decimal digits and allow exponents up to 9,999. These limits were chosen because they match certain characteristics of the processor. A 600-digit mantissa, a four-digit exponent and their signs can all be fitted into 256 bytes; in the 6502 a block of 256 bytes is one "page" of memory.

In Robinson's programs the operations that can be carried out on numbers include the elementary arithmetic ones as well as the logarithmic, exponential, square-root and various trigonometric functions. Some less common functions are also provided, such as the Euler and van Wijngaarden transforms for summing slowly convergent series. Recorded in the package are the values of some 26 constants and 8,000 prime numbers. It can be used as a highly accurate desk calculator, or the functions can be called from within a program. Prelimi-

nary versions indicate that the arithmetic operations and the functions are accurate up to the limit of 600 digits.

For those interested in numerical calculations a first acquaintance with the digital computer is sometimes disheartening: because the machine's elementary calculations are fast and essentially flawless, the naive expectation is that elaborate numerical analyses can be done with great ease. One is then disappointed to learn that the fifth root of 100 (the quantity astronomers designate an order of magnitude) cannot be determined with much greater accuracy than a hand-held calculator provides. A package of programs such as Robinson's redeems some of the computer's promise. The fifth root of 100 can be calculated to 100 decimal places in a matter of minutes.



Flow charts for the calculation of the 39,751-digit prime number $2^{132049} - 1$

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BOOKS

Time machines, the first biosphere, the Mayas, the Titanic iceberg, sweeping Swiss panoramas

by Philip Morrison

REVOLUTION IN TIME: CLOCKS AND THE MAKING OF THE MODERN WORLD, by David S. Landes. Harvard University Press ($20). We find ourselves at the close of a historical era seven centuries long. Mechanical timekeepers large and small have entered on their obsolescence. They are far from obsolete, but the new epoch of quartz and the pulse-counting chip has plainly opened. The big bar swinging in and out of the teeth of its crown wheel as the weights descend in the tower, like the elegant balance wheel swinging unseen at the wrist, are now inferior, both technically and commercially, to the electronic devices. Although gears come from the Greeks, although timekeeping by sun shadow and water flow descend to us from dim antiquity, it was the clock and the watch as mechanical oscillators that ticked out the long rise of Europe to industrial dominion.

Chips were cosmopolitan almost from the start. An excellent digital watch today might well have been quickly assembled in Malaysia by clever and hardworking young women from components from California, Switzerland and Japan. In 1968 the Swiss Council of State suspended the time-trial competitions customary for more than a century at Neuchâtel for the commercially important category of production wristwatch chronometers. The trials have never been resumed; Swiss horology refused to accept "even the possibility of a defeat on its own ground." Switzerland still rivals Japan in the output of watches and components, much of it now electronic. But the Swiss hegemony over watchmaking, fully a century old, will not return.

That Swiss success is retold and analyzed in a fascinating hundred pages of this book. The narrative begins with the French Huguenot emigration to John Calvin's straitlaced Genevan republic. Until early in the 18th century it was Geneva that was the Swiss watch, its commercial enterprise unmatched, its craftsmen skilled and diligent. The trade prospered. Thousands of artist-artisans worked at their benches in the small shops, the merchants bringing in the work and taking it out again, all sensitive to the tastes of distant markets. Watches that were shaped like fruits or like pistols, musical watches, erotic watches with scenes animated by the balance wheel, all were fine products from Geneva.

Northward in the Haut-Jura the pastures and fields were never rich. There people lived hard and frugally. Watchmaking as a cottage industry entered to absorb the labor of the entire family through the long isolating snowy winter; it replaced lacemaking for women and children because it paid better. Wheels and pinions, plates and arbors, dials and cases all could be made in the home to pattern with hand-driven tools once the tasks were minutely subdivided. It was said that before 1800, 150 workers contributed in one way or another to the making of a single watch. (The remark seems to be an exaggeration; Professor Landes believes 40 would be closer to the truth.)

In the region of Neuchâtel, "notwithstanding the... severity of the climate, beautiful and well-built villages are everywhere to be seen... with a very considerable population, in the enjoyment, if not of great fortunes, at least of a happy and easy independence." So wrote a British observer to Parliament in 1836. The herdsmen of the Jura had pliable hands, not the horny ones of plowmen; everyone there could qualify for watchmaking (save those few whose hands perspired and stained the metal). Even the weak-eyed were recruited and furnished with loupes and condensers to focus the lamplight. Above all, the Jurassiens were Protestants. It was not a matter of mere diligence, as Max Weber might have had it. Rather, it was universal education in letters and numbers that made the difference. All the boys and girls could read and cipher and could easily learn to measure. Among the many were people ingenious and inventive enough to become masters, to take on the expert tasks of finishing and regulation that not every cottager could complete. The watchmaking of the Jura, world leader for a century and more, was no simple affair but a collective achievement, as much cultural and social as it was economic.

Before the Swiss it was the British countryside that held watchmakers. Chronometers aside (the cross-channel rivalry in that long tale of virtuosity is well put here), the British lead in the 18th century was driven by demand. In its time that demand called forth an eight-mile stretch from Prescot to Liverpool, "dotted with the cottages of springmakers, wheel cutters, chainmakers, casemakers, dialmakers." It was as exemplary a division of labor as Adam Smith ever knew, bringing within a century a twentyfold reduction in the price of a watch movement and at the same time an improvement in quality.

The demand, "precocious... and socially diversified," was stimulated early by self-conscious workers in Britain's thriving new textile factories. These were people whose time was not their own. Their days were partitioned now by the millowner, not by the weather and the season. But only the clock-holding employer could count the work hours; the employee had to take his word for it. Was the clock under manipulation to cheat the workingman? It was clear that not all mill clocks agreed. In such circumstances there is a piece of satisfying self-help to be found in a cheap silver turnip watch, bought perhaps for a fortnight's wages by a thrifty man or by a pool of friends. Output grew swiftly.

The largest section of this book, sampled above, is a major contribution to economic history for the general reader, graceful and full of wit, fresh and scrupulously documented. Two other sections precede it. The first 80 pages, a broad cultural speculation, treat of the enigmatic origins of the clock, how and why it appeared in late medieval Europe. The second section is an essay in the history of science and technology, the story of the 500 years of evolution from the heavy turret clocks to the chronometer and watches cheap and fine, from "dials with one hand to dials with three." The story here is less novel but nonetheless full of interest, with its pendulum studies and ruby bearings, its watch oil and tempered spring steels and an entire suite of mechanical ingenuities. The rich horological literature, which centers on this domain when it is not simply a catalogue of antiquarian minutiae, is well used and given clarity not easily found elsewhere.

It is a fact that no mechanical clock can be documented in detail earlier than about 1320, the time of Dante Alighieri. The first such clocks we know, however, are already grand examples, turning entire planetariums, fitted with moon dials and performing automata, bearing all the signs of a well-mastered art. Landes puts forward good arguments, even if they are still short of proof, that the mechanical clock came into service not long after 1250. It is then that the

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profession of *horologium* first appears, that the cathedral chapters begin to pay for clock maintenance and improvements and to appoint officers to deal with such tasks.

These clocks that we glimpse only peripherally are recognized wonders, matters of pride. They are plainly large, and occupy rooms high in some tower. "And what is a clock, but a bell?" The clocks were indeed bell ringers, their function first to sound the necessary alarm of the hours set for prayer, particularly the midnight matins and the dawn lauds. It is some 100 years from these earliest inferred alarm clocks to an astronomical clock as wonderful as that finished by Giovanni de' Dondi of Padua in 1364. Before this period of clock consciousness the monasteries had all used ordinary water clocks, as people had done since antiquity.

The case is strong that something had changed, that mechanical clocks had come to rule the bells that in turn controlled the economic beehive of industrious and dedicated brothers. We cannot, however, quite see that first escapement quivering as it beats the seconds. It seems probable from this account that clocks did not appear first as "fallen angels": practical devices simplified from the more elaborate celestial models that are all we know for certain of early clocks. A Chinese stimulus, arising in a kind of water-driven escapement known to have been realized on a towerlike scale by the astronomers in Sung China before 1100, might have played some suggestive role, although evidence is entirely lacking. The author views both unusual proposals with pungent incredulity. To his mind social need must come first: "Some people ... wanted very much to track the time—not merely to know it, but to use it."

Yet necessity is not a fond mother to fundamental invention; her heart belongs to quick new combinations. A heated water clock might well be devised to answer the northerner's need to summon to prayer, but a verge-and-foliot escapement? Perhaps some clever millwright starting with a bell-ringing water clock did find his own way to that genuine revolution in time. A reader is left musing, thinking, say, of Wilhelm Röntgen's X-ray pictures, first published in 1896. If we had no documents from 1895 and before, might not historians make out a strong case that railroad wrecks and colonial wars had created a demand for seeing broken bones?

This is a splendid book, its author a proper historian, learned and analytical. He was drawn from economic records of larger matters into the domain of elegant wheels and fine springs by a collector's passion endured over 25 years. The book's brilliance should glow for a long time before many readers; this history of timekeeping does track the history of our modern world, to the last tick and beyond.

EARTH'S EARLIEST BIOSPHERE: ITS ORIGIN AND EVOLUTION, edited by J. William Schopf. Princeton University Press ($95). A heavy, handsome book joining reviews and fresh research reports on some current topic is often the output of a brief, well-planned international conference. This one is an exception: the two dozen contributors are linked not only by the usual ties of those who follow a discipline but also by a tighter bond. They had been gathered together by the editor—a micropaleontologist, one of the best-known research workers in the group—from their laboratories around the world to work as an expert team. About half of the group spent more than a year in interactive residence at the University of California at Los Angeles, and afterward they came together at frequent meetings and exchanges before this summary symposium on the three years of their joint work, to which the Precambrian Paleobiology Research Group (P.P.R.G.) invited about 120 other chemists and biochemists, geologists, physicists and microbiologists. The gathering was a happy and successful one, whose spirit shines throughout this technical and comprehensive volume.

Informed by, but never resting on, plausible theoretical models of the planet-forming and geologic processes of the deep past, these studies are a search for fossil evidence of earliest life, at the isotopic, biochemical, microscopic and plain eyeball levels. The entire book is strung tightly on a chain of radioactive dating not explicitly examined here. Those dates fix the assembly of the earth at about 4.5 billion years ago. The oldest rock samples are from the western shores of Greenland; they are dated 700 million years later than that. Those rocks are much modified by later folding, cooking and intrusions, but they are not extraordinary in any way. That past was different, but the differences were subtle ones, in atmosphere, day length, temperatures, life—not to be grasped easily from the rock fabric. No unquestionable life forms are to be found in those rocks, although their presence had been averred. The small rounded images seen as cells grade rather neatly, however, into angular, plainly crystalline inclusions along grain boundaries in the rock—no likely site for life.

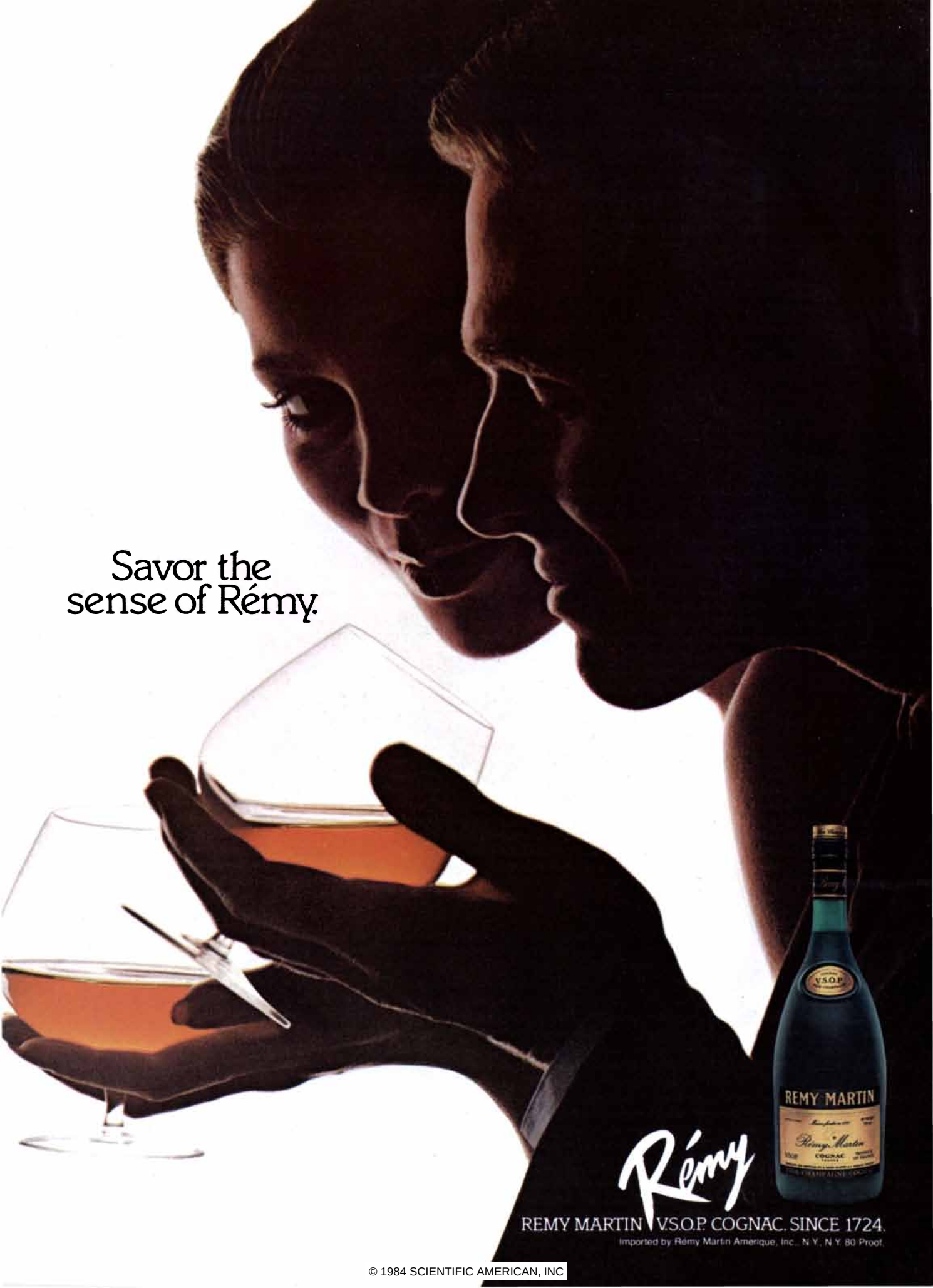
Such exciting false alarms are nothing new: in the 1880's a Paris microscopist of "legendary skill" identified 20 genera of radiolarians in preparations he had made from very old rocks. His slides were reexamined in 1980 by Preston Cloud, who contributes a fascinating historical summary to this volume. The images were so hard to make out that the early investigator assigned an artist who had never drawn radiolarians to draw what he could see in the key section. The artist in his zeal seems to have done some unassigned homework; his drawings, full of imagined detail, supplied material for the copious "identifications."

Now we definitely know very old fossil cells. The interesting photographic section of the book shows them: long, branching bacterial strings, quite convincing in form, location, variety and size. They lived 1.0 billion years after the beginning of the earth. These are the first organisms known. The very microlayers that hold these bacteria, however, belong to the layered structures called stromatolites, big as cabbage heads, certainly the remains of a bacterial mat of a complex kind, living in shallow salty water, calcareous, motile and quite possibly photosynthetic. The specimens are shown in a color photograph; they resemble their counterparts today, some of which are found in brackish coastal waters of western Australia not far from their ancient fossil kindred.

It is elemental oxygen that is the topic of the most complicated discussions in these pages. The main facts today are plain: oxygen is the product of photosynthesis, and the store of that reactive gas we breathe on the life-quickened surface of the earth today is cycled and recycled with explosive speed, within a few parts per million of geologic time. It was not always so. The key evidence appears to be that of the banded-iron formations, so widespread as to be a major source of iron ores. They are layered sedimentary rocks in which dark bands of iron compounds alternate with the siliceous matrix. Although we are far from a full understanding of these rocks, they imply a source of oxygen enough to convert into insoluble ferric material the ferrous solutions that must have first formed the flat, continuous horizontal layers that can in some sites be traced over hundreds of kilometers.

Our world was then a reducing world: oxygen-poor waters, oxygen-poor air. It was not, however, oxygen-free; the bands represent a large sink for the reactive oxygen. From the earliest banded irons, which are about the same age as the first bacterial cells seen, 700 million years A.F. (after the formation of the earth), until such rocks cease to be widespread, 2.8 billion years A.F., free oxygen must have been rare. After that the iron deposits are red, richly oxidized; oxygen gas was a commonplace in air and water, as it is now, and modern plants (such as the green algae) and one day even animals—all animal life, of course, depends on this active cell poison—could thrive in distant but inescapable interdependence.

It used to be argued that before the banded iron there were simply no photosynthesizers; that now seems a hasty



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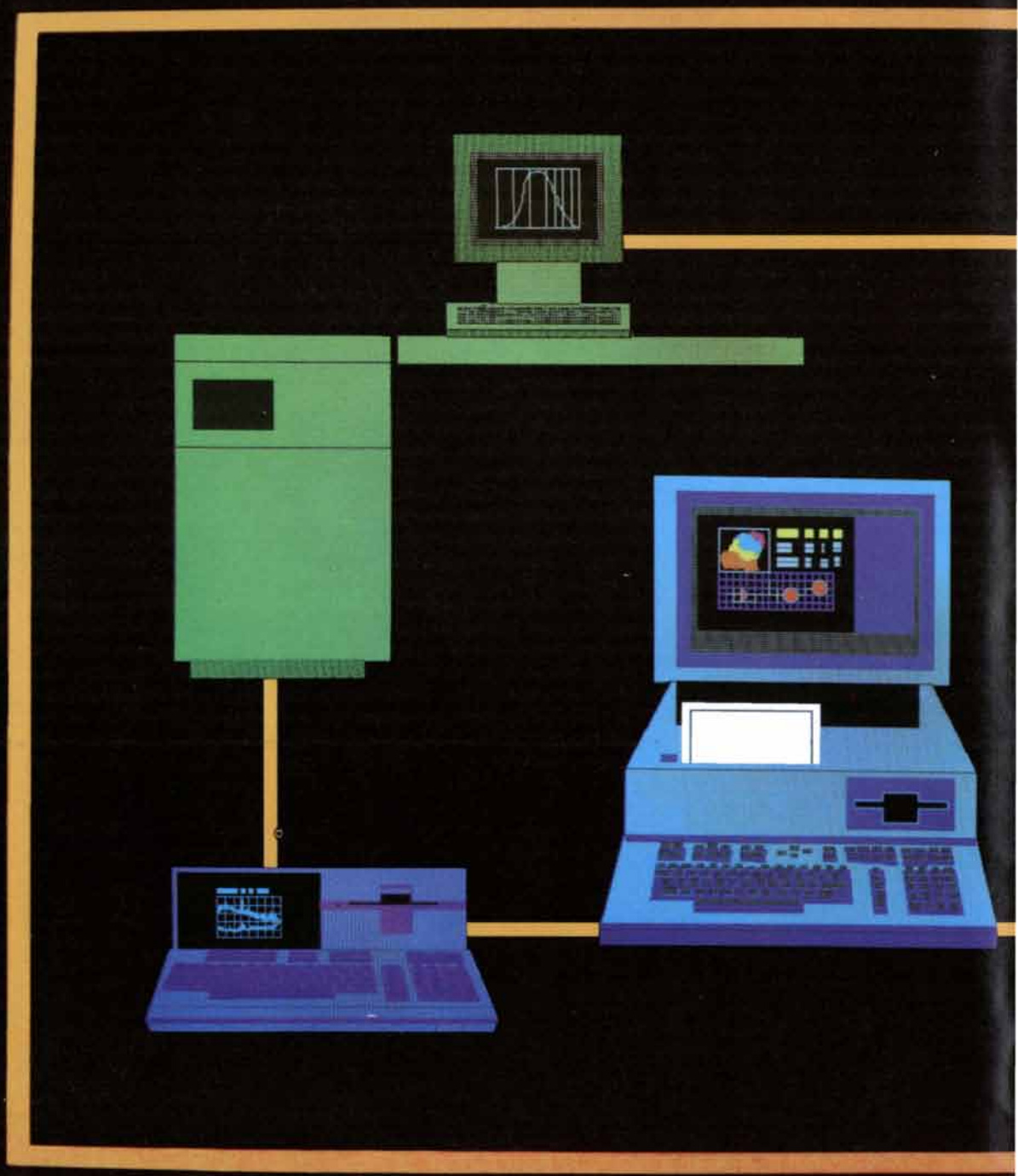

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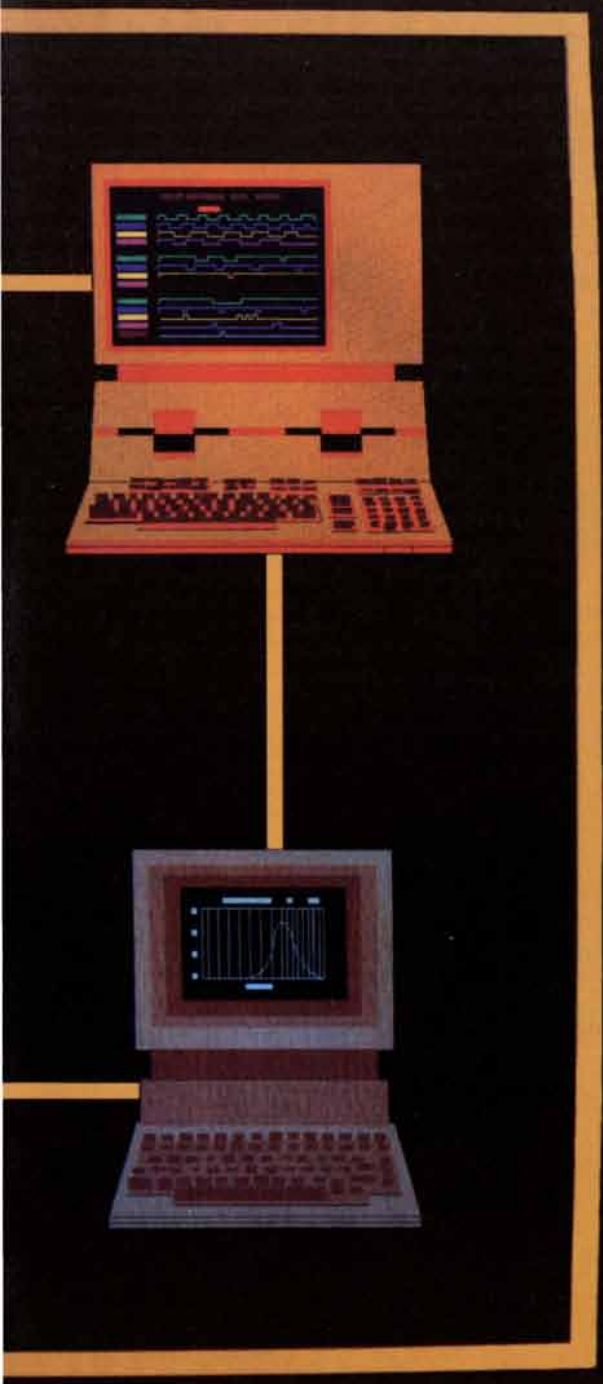

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conclusion. P.P.R.G. is more judicious: the first cells we know, with the stromatolites they or their contemporaries built, may well have made and used oxygen sparingly, as the inorganic banded iron suggests and more complex arguments from biochemical analogy confirm. The relevant paper notes "seven metabolic benchmarks." Only much later did oxygen abound; then "the atmosphere and oceans would have been swept free of reactive reduced compounds" and the modern green and breathing world arose. In today's world oxygen is entirely under biological control; in that antique time oxygen remained largely regulated by inorganic processes, such as volcanic emissions and stratospheric photoreactions. The ozone layer, our ultraviolet shield, is part of the oxygenic epoch; before that time life had to seek shelter from the sun, say under shallow layers of water.

There is here a well-supported overall "best guess." By about 0.6 billion years A.F. the cannonade of meteorites natural to the early solar system had ceased. Life arose not later than 0.7 billion years A.F., and possibly much earlier, in a subtly strange environment. That world of early life was as watery as the world is today, and it was salty too, in lakes as well as seas. Dry land was present as granite rock, perhaps not yet in continental masses but in islands. The tides were somewhat higher than those we know and the days were shorter. There was already a magnetosphere to exclude the cosmic rays, but no ozone layer. Carbon dioxide was present, perhaps even abundant, but the air was mainly nitrogen. Temperatures were not abnormal. The shores bore life, invariably close to the water, life fit for an environment that differed mainly in its strong flux of ultraviolet and its low oxygen.

Life then slowly became abundant, biochemically diverse and powerful, complex but lowly, still dependent on liquid water, organized at most into colonial mats and mixed populations of single cells. About 2.8 or 3.0 billion years A.F. millimetric forms of life at last appeared, small, flattened fossil algal spheres, first reported from the Grand Canyon of the Colorado just 100 years ago. Here we are at 4.6 billion A.F., puzzling it out slowly, at the top of a timetable that indicates and tentatively interprets about 40 salient events. First of all the earth accreted and its dense core gathered, to release all that gravitational energy to stoke the geologic furnace. The terrestrial smelter worked to outgas air and water from the fused and separated slags, now the mantle and the crust. The great globe spun, formed and ready for life.

THE ANCIENT MAYA, by Sylvanus G. Morley and George W. Brainerd. Fourth edition, revised by Robert J. Sharer. Stanford University Press ($28.50). Between the narrow waist of Mexico and the western part of Honduras there live about two and half million people, mostly village farmers, who speak at home one of a couple of dozen closely related languages. These are the modern Mayas, linked now to the rest of the world. Within the same diverse tropical area, across its lowland plains and high rain forests and along the coasts of two oceans, a couple of hundred important archaeological sites are known, the works of the ancient Mayas. The dawn of settled life there around the gardens and the fields of corn goes back 4,000 years. It was less than 500 years ago, however, that Christopher Columbus on his last voyage in the Gulf of Honduras encountered at sea a great trading canoe of the coastal Mayas. That meeting was the Mayas' first with Europeans; it took nearly two centuries for the final conquest, until in 1697 the Spanish forces reduced the last stronghold of the redoubtable Itzá Maya, on an island in a Yucatán lake. A long time of trauma had ended and a brand-new volume of history had begun.

The old Mayas built across their lands the most enduring civilization of the New World. First the resolute travelers, then scholarship and the spade—or the machete—revealed the great abandoned white towers in the green forests, with much more. "What we do know about these once enigmatic people is prodigious," and our knowledge has flowered within the past decade. This volume, as readable as it is comprehensive, is an admirable and up-to-date account of the ancient Mayas we now know. The book is itself a kind of archaeological structure; its logical and contextual foundations were well laid by a gifted pioneer in Mayan research. Sylvanus Morley excavated Chichén Itzá between 1924 and 1940; near the end of his career he published in 1946 and 1947 two editions of his clear and comprehensive study for the general reader.

After Morley's death the book was revised within a decade by Brainerd; new finds at Palenque, Bonampak and elsewhere demanded it. At that time, however, Tikal, the largest and now the best-investigated of any Mayan site, was hardly known. Morley himself had recorded its hieroglyphs, but the Tikal project of the University of Pennsylvania has since 1956 undertaken 28 volumes of reports, almost half of them already completed. Tikal was, after all, a city of 100,000 that thrived for 500 years. The author of this fourth version of Morley is an archaeologist at the University of Pennsylvania, himself an experienced excavator at Mayan sites and a thoughtful and productive synthesist.

The book has four well-illustrated parts; the photographs and diagrams, in black and white, are carefully chosen more for substance than for appearance. The parts include the cultural history of the Mayas, the setting, origins and periods we now distinguish; Mayan society, particularly subsistence and everyday life; the material culture, from the grand structures and sites to handcrafts, particularly ceramics, and the intellectual culture, particularly language and the writing recently deciphered in part, with an epilogue on the protracted and cruel conquest.

The vigorous coastal trade of the Putun Mayas was a feature of the final period of ancient Mayan history. They traded along the Gulf Coast many hundreds of miles south from their home in Tabasco in Mexico. Their oceangoing canoes had both paddlers and sails; the craft transported goods far more cheaply than bands of porters inland, or even canoes on the interior rivers, which called for many portagers. The canoe Columbus met was, he reported, as long as a galley and eight feet wide, with a cabin amidships and a crew of two dozen men. Its cargo included cacao, copper bells and axes, crucibles and other pottery, cotton clothing and swords of wood with an obsidian cutting edge. Like the Mayan written documents, the Mayan seagoing canoes suggest a delayed Mesoamerican convergence toward the civil accomplishments of the Old World. Would some Mayan Columbus eventually have sailed eastward across the Atlantic, supposing that the cultural delay had tilted the other way by 2,000 or 3,000 years?

From this thorough account let us pick up a few of the new conclusions of the past couple of decades. Much thought has been given to the cause of the decline of the Classic lowland Mayas. In the ninth century of our era that brilliant civilization seemed to come to a halt. After 500 years of growth in center after center, construction ceased, the luxury and ritual trades ended, the dated monuments were no longer built. Hypothesis after dramatic hypothesis has been formed and found wanting. Neither peasant revolt nor foreign invasion finds evidence in support. It seems now that it was always a fallacy to imagine a single sharp cause; instead, more or less by chance, both external influences, such as the decline of trading partners, and internal ones, such as cyclical prophesies of change and increased taxation by the elite, coincided to enforce a subtle and swift cultural decline.

The Mayas of today practice slash-and-burn agriculture, the fallow fields waiting a few years for a new stand of corn. It now appears that this was not their only ancient technique. Such a foundation could never have supported the population density disclosed at some sites. Careful work has uncovered evidence of several kinds of more intensive agriculture, including raised fields sur-

rounded by water fed by systems of irrigation canals. One splendid aerial photograph is compelling; it shows relic fields among old canals in a fine muddy site in Belize, known by the wonderful name of Pulltrouser Swamp.

It was in the late 1950's that the perceptions of Heinrich Berlin and Tatiana Proskouriakoff opened up the Mayan inscriptions. Until then the scholars for all their work had only dates: dates by the hundred, dates exact to the very day but dates alone, with no knowledge of what happened on any date (except for certain—admittedly quite wonderful—astronomical phenomena that could be inferred from lists of dates alone). Proskouriakoff realized that many groups of stelae had been set up in a dated order, year after year. There is always an early date, just before the date of erection of the first stela, and another date a few decades later. Each of these dated slabs had certain particular glyphs along with the date. No group ever spanned more than some 60 years.

The interpretation worked: these were birth dates, dates of accession and anniversaries. The ruler and his consorts are depicted, not the gods and the priestly female impersonators earlier assumed. Proskouriakoff's brilliant interpretation is now widely accepted; in such carved slabs there is the formal history of a ruler. Further progress was made by the Russian linguist Y. V. Knorozov, who argued for the phonetic or syllabary nature of many Mayan glyphs. His scheme, less quick to gain adherence, has since been strengthened by several other workers.

Today Mayan writing is seen as a blend of word and syllable signs, becoming increasingly phonetic over time. A couple of texts are shown here in glyphs, along with the best current translations. All this advance in decipherment has gained us so far "nothing but the most boring sort of history," sculptured lists of rulers and the formal events of their lives, but that is better than the meager diet of dates alone. The fires of the Spanish zealots and the wetness of the climate have combined to leave us only a handful of Mayan codexes on bark paper, longer texts than the carved monuments, to be sure, but pitifully few and all more or less merely almanacs.

A few pleasures for the reader go back to Morley. There is a set of drawings made in the 1950's by the French artist Jean Charlot that offer a witty and convincing look at how the Mayas quarried, moved, erected and carved their big stones, all with stone tools and clever rigging of rope and timber. The round of daily life is also vividly presented. The Mayan women still prepare maize tortillas daily, in five dexterous steps that make ready the staff of life, as "doubtless was so in the past" (although a hand-cranked rotary metal mill replaces the reciprocating grindstone of the past for making the cornmeal). Finally "a round, thin, flat cake rapidly takes form under her fingers. The almost continuous pats produce a characteristic sound, heard throughout all Maya villages at midday." Tamales were perhaps more typical before the conquest than tortillas, which have a Mexican origin; it is, after all, the tamale that the Mayas favor today for ceremonial meals. The early chroniclers also report that the main meal was served "an hour before sunset." The modern Mayas are of course not an ancient people; they have a distinct culture, with the Old World powerfully shaping and informing the New. Still, there are invariants, even under that insistent transformation.

VOYAGE OF THE ICEBERG: THE STORY OF THE ICEBERG THAT SANK THE TITANIC, by Richard Brown. Beaufort Books, Inc., 9 East 40 Street, New York, N.Y. 10016 ($13.95). Every collision has at least two partners. The *Titanic* has had its due share of ink, and more; after 70 years it still displaces more symbolic tonnage than any other vessel out of the Belfast shipyards. Here it is the partner's turn, the long-ignored iceberg. One photograph, taken at sea the day after the encounter, shows the very berg, if we are to credit the report of a scar of paint as red as the *Titanic*'s new hull along the base of the ice. In this small and many-stranded net of gleaming stories the 18-month life of that piece of floating ice is followed from its calving in the north to the day its last remnant melted into the warm waters of the Gulf Stream. From time to time the narrative offers a vignette on the world of the White Star Line and the legal complement of lifeboats. "Most of this book is true"; only a little is drawn from surmise or conjecture. Nearly "every man and ship I name was doing what the book says."

The drama is played out mostly on the long complex arm of the sea that separates Greenland from the large islands off Canada, a body of water opener than the latitudes imply, thawed by a northward thread of the Gulf Stream. The tides there launched the iceberg. A solid tongue of ice, part of the fast westward flow from the mighty ice cap, pressed out into the cold waters. One September ebb tide the ice hinge at last cracked through. The million-ton iceberg was launched, one of a flotilla of 10,000 large and small bergs set adrift every year in Baffin Bay. This one would circle like the rest against the wind north into the high Arctic, then far southward again past Labrador to cross the tail of the Grand Banks to the shipping lanes, there to groan and splash, to capsize and turn again and again, finally to melt away into warmer waters after its brief encounter with steel afloat. The berg's journey was not much farther than the ship's, although it was much slower and filled with event.

The unfolding surprise of this artful book is how much of life the ice encounters as it sails blindly on. Knud Rasmussen, poet and hunter, can see the berg as it passes, of course without marking it out from the rest of the craggy parade, as he makes a rare seaside journey southward that first winter of the berg's life. Later the women are out from Thule on a summer evening amid the feathery piles of little birds, the dovekies that abound there, easy to hunt, plenty of fat food for the packing, small skins to be chewed to pliancy for hunters' shirts. The berg drifts past the wily old bowhead whale, last of its species in the open North Atlantic; Captain William Adams has taken seven other bowheads this season, the last ever for whalers there. The berg grounds about where men fight and die over walrus hides off Baffin Island in the fall of 1911.

Just before the berg's first sea roll, about a year after its birth, when it turns turtle to come up in new form, diminished now and water-rounded, the research barque *Arctic* by great good fortune misses colliding with it—or a sister berg. In March of 1912 the berg drifts close to the Labrador shore, past that spring's bloody clubbing of the little whitecoat seals, past the tiny Funk Islands where once the great auks roosted, until one midnight at the far edge of the cold current, while it rolls slowly in the swell, a swift hull glances along the ice edge. The foot of the berg opens a slit 300 feet long in the steel plates, "as a knife guts a fish." The gash is above the bulkheads planned to make the ship unsinkable, but it is still below the waterline. The iceberg rocked and spun a little, to carry away only a paint smear from that one point common to two tracks, at 41 degrees 44 minutes north, 50 degrees 24 minutes west. The ship remains invisible not far from there; the iceberg is of course truly gone.

Even the high Arctic has changed a great deal since 1912; the area is busy every summer with helicopters, oilmen and scientists. Isolated Thule became a busy air base, although even that is changing as more missiles are buried on the windy plains along the Missouri. "But some things do not change. The dovekies still come pouring off the slopes above Parker Snow Bay in millions. And the icebergs keep calving into Jakobshavn Ice Fiord."

Richard Brown is a marine biologist from Halifax, an Arctic traveler among carpets of flowers by summer and among ice diamonds by winter and an adept of the vivid image put in quiet words. He scrupulously identifies the three dozen striking illustrations he has chosen and then lists a few more books to read. "But be very careful: the Arctic

is a dangerous drug and you may end up as hooked on it as I am."

SWISS PANORAMA, text by Emil Egli and Emil Schulthess. Photographs in color by Emil Schulthess. Alfred A. Knopf, Inc. ($50). Schulthess is the Swiss landscape photographer who a dozen years ago took a celebrated 360-degree Alpine panorama published as a color poster two and a half meters long. It showed the snowy peaks around the highest point in the country, the 4,600-meter Dufourspitze. The helicopter that had the night before brought the intrepid photographer to his precarious perch is in the photograph, not casually present but essential: the aircraft was poised in hovering flight just so that it would shadow the camera lens from the direct rays of the sun. Without it the scene would have been ruined by dazzle.

That single tour de force reverberates in this remarkable volume of new photographs. Schulthess has made many panoramic views of the varied Swiss landscape over the past eight years. We form an idea of what is going on from a shot made over Zurich. The reader looks from 20 meters away straight at one big dial of the clock in the St. Peter's Church, in the center of the city that fills the rest of the 360-degree scene. There is no such solid vantage; the camera hung in thin air. Like the other pictures in this book, the image was made with a special gyro-stabilized rotating camera under remote control, suspended by long cables below a helicopter flown with precision by the Swiss Air Force. The picture is big; it covers four long pages of the book in a double gatefold.

The book presents 28 panoramas in all, the smallest of them a two-page spread. There are five more gatefolds, about four feet long. They are all helicopter-borne views of Switzerland: towns and fields, lakes and forests, a castle and a cooling tower, and of course the high spectacles of icy peaks and snowy cirques. The views are not all complete circles; a few are "looping" panoramas, with the camera rotated in the vertical plane, showing a view from horizon to horizon. The Great Aletsch Glacier appears in its striped slow flow out of the Jungfrau; the city of Bern is tidily mapped in the center of a landscape that reaches from the Vosges on one horizon to the Apennines on the other, with the Alouette helicopter at a near-record altitude of 6,200 meters; the towering needles of Mont Blanc are close at hand.

The book includes a narrative of the risks, ingenuity and plain hard work needed to achieve these images. There are index photographs and careful maps of the views shown, and a trilingual description of each scene and its challenge. The work is altogether a pinnacle of enterprising photography.

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Breast Feeding

Its contraceptive effect is increasingly forgotten in the worldwide trend toward bottle feeding. In many developing nations the result is a rise in the rate of population growth and poorer infant health

by R. V. Short

Breast feeding is nature's contraceptive. In ancient times it was common knowledge that a woman who was nursing a baby was unlikely to conceive in that period. Today the fact that breast feeding can still play an important contraceptive role has become little more than a myth in the minds of many people. The change has had serious consequences for rates of population increase and for infant health, particularly in many developing countries.

In developed countries breast feeding is generally viewed as an aftermath of human reproduction, an optional extra tacked on at the end, like the credits for a motion picture—of importance to a few but unlikely to arouse much general interest or excitement. It is a topic that has been largely ignored by the medical profession. No medical specialty takes responsibility for it. The obstetrician's job is over once the baby has been delivered and the mother has been discharged from the hospital; the gynecologist would hardly regard the breast as being an integral part of the reproductive tract; the pediatrician is usually more concerned with the care of sick infants than with the establishment of breast feeding by the mother in a normal home environment, and few family-planning physicians would think of advocating breast feeding for its contraceptive effects.

Therefore it is often the general surgeon who has by default become the breast specialist, since breast cancer is the commonest human neoplasm. Some surgeons go so far as to recommend removal of the breasts and their replacement with silicone prostheses as a means of preventing the disease. Thus it is not surprising that breast feeding attracts little attention in medical textbooks and classrooms and hence little research interest. Society knows far more about the udder of the dairy cow than it does about the tender human breast.

The failure of physicians, scientists, theologians, administrators and politicians in developed countries to appreciate the full significance of breast feeding for the spacing of births and the health of infants has had serious consequences for developing countries. Recent estimates by the World Health Organization suggest that only an overall 17 percent of the couples in developing countries are using modern forms of contraception. Therefore 83 percent are entirely dependent on natural checks to their fertility, of which breast feeding is by far the most important.

The recent World Fertility Survey organized by the International Statistical Institute in London showed that in many developing countries today young women who are educated, urban and affluent are abandoning breast feeding in favor of bottle feeding. Since they are the trend setters in their community, their influence is spreading to the urban and rural poor women, who are the least likely to use modern contraceptives and whose infants have the most to gain from breast milk.

Ron Lesthaeghe of the Free University of Brussels has calculated that in Bangladesh, where only 9 percent of the women now use contraceptives and the mean duration of lactational amenorrhea (absence of menstruation during lactation) is 18.5 months, the use of contraceptives would have to rise to 43 percent just to hold fertility at its present level if lactational amenorrhea were to decline to six months. In Kenya, where only 7 percent of the women use contraceptives, much of the recent sharp rise in fertility to the present average level of about eight births per woman can be attributed directly to a decline in the duration of lactation. Since it is extremely difficult to generate a rapid increase in the use of contraceptives in such countries, it is essential meanwhile to prevent further erosion of the contraceptive effect of breast feeding.

It would be wrong to blame the manufacturers of powdered milk for having initiated the trend away from breast feeding; it began centuries ago. They must bear much of the responsibility, however, for perpetuating and facilitating the trend in developing countries today, to the detriment of maternal and infant health. The fact that the U.S., where many of the powdered-milk companies are based, was the sole nation in 1981 to refuse to endorse the WHO's recommended International Code of Marketing of Breast Milk Substitutes, which would limit the aggressive advertising and sale of powdered and condensed milk, tells its own story.

In order to understand the critical role of breast feeding in human reproduction one should view the subject in an evolutionary perspective. One of the keys to the success of *Homo sapiens* is the retardation of the species' rate of reproduction. This has resulted from the postponement of puberty until well into the second decade of life (something that is unknown among other mammals) and from the prolongation of the interval between successive births through the contraceptive effects of breast feeding.

These reproductive restraints have opened up new horizons for human evolution. The development of the large human brain, which is incompatible with birth through a narrow pelvic canal, has to take place after birth, making the infant totally dependent on its mother for a prolonged period of time. With the

postponement of puberty came an extended period of childhood, providing an opportunity for the parents to impart a wealth of acquired knowledge to the child. It is this ability to transmit information as well as genes that has given the human species ascendancy over all other mammals.

It is useful to recall the environment in which these reproductive restraints evolved. The human species has spent more than 90 percent of its existence leading the life of nomadic hunter-gatherers. Although that way of life has largely vanished, the fact remains that in their genes people are still hunter-gatherers; "civilization" is too recent to have had any appreciable impact on the human genetic makeup.

The best clues to that vanished existence come from studies of the few remaining hunter-gatherer societies in Africa, Australia, New Guinea and South America. By far the best-documented are the !Kung of the Kalahari Desert in southern Africa, who have been studied by Richard Borshay Lee of the University of Toronto and Irven DeVore of Harvard University and their students. Nancy Howell of the University of Toronto has shown that the !Kung, who use no modern forms of contraception and have no fertility-regulating practices such as late marriage, taboo on intercourse during lactation or infanticide, have an average completed family size of 4.7 children and a mean birth interval of 4.1 years. If mortality is taken into account, one can calculate that it will require about 300 years for the population to double.

That these long birth intervals are achieved by breast feeding is evident from the fact that if the infant dies and lactation ceases, the mother is soon pregnant again. Studies by Melvin Konner of Harvard and others have shown that the mother carries the infant wherever she goes and that it sleeps beside her at night. The infant suckles frequently during the day (about four times per hour), although each feeding lasts for only a minute or two. The infant also suckles frequently at night, even when the mother is sleeping. If the mother gave birth oftener than once every four years, her freedom of movement would be severely limited and a nomadic existence would become impossible.

Although this high frequency of suckling may seem abnormal at first, there are several reasons to think it probably represents the human norm. A similar pattern has been found among hunter-gatherers in Papua New Guinea. Moreover, the pattern would be in keeping with the biochemical composition of human milk, which is low in fat, protein and dry matter. Species that suckle their young less frequently (cows, sheep, goats, deer and rabbits among them) have more nutritive milk. The human species' closest living relatives, the chimpanzee and the gorilla, also suckle their young several times an hour in the wild, secrete a milk quite similar to human milk, sleep with the infant at the breast at night and have a birth interval of four or five years.

The precise mechanism by which suckling inhibits fertility is not fully understood. Certainly it is the suckling stimulus itself, rather than the production of milk, that is crucial. Experiments with sheep and wallabies have shown that if the teat is surgically denervated, lactation continues normally but the contraceptive effect of suckling is lost.

My colleagues and I have been able to show that in women the sensitivity of the nipple increases markedly at the time the baby is born. The phenomenon may be important for enhancing inhibitory inputs to the brain. It is well established that the act of suckling provokes a reflex discharge of the hormone oxytocin from the posterior pituitary gland; the hormone causes the contraction of the myoepithelial cells surrounding the alveoli of the mammary gland and hence the ejection of milk. Suckling also causes a reflex discharge of the hormone prolactin from the anterior pituitary gland; this hormone is thought to be important for the long-term maintenance of milk secretion. Thus oxytocin serves today's meal and prolactin prepares tomorrow's. The more frequent the suckling, the higher the level of prolactin.

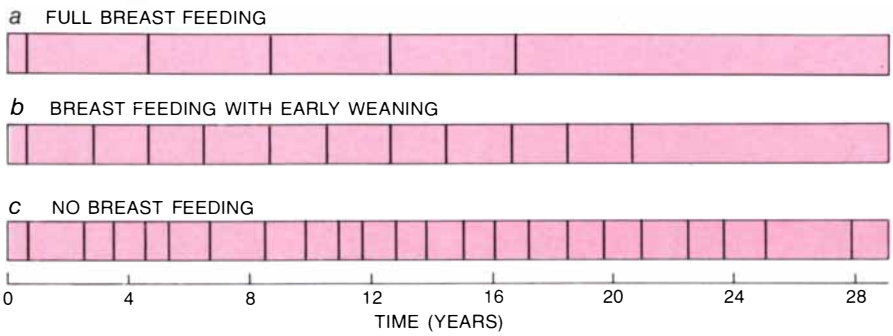
Women who have prolactin-secreting pituitary tumors usually do not ovulate or menstruate. Their secretion of luteinizing hormone (an anterior-pituitary hormone that causes ovulation) is depressed. If the tumor is removed surgically or the secretion of prolactin is inhibited by the drug bromocriptine, the secretion of luteinizing hormone soon returns to normal, followed by a resumption of ovulatory menstrual cycles.

This chain of events has led to the widespread belief that the high output of prolactin during lactation inhibits the secretion of luteinizing hormone and may also have a direct inhibitory effect on the ovaries, thereby suppressing ovulation. The view is open to question, because rhesus monkeys in which the secretion of prolactin has been suppressed by bromocriptine will still not ovulate if the infant continues to suckle. Moreover, women with amenorrhea arising from an excess of prolactin resume normal secretion of luteinizing hormone when they are treated with naloxone, even though the level of prolactin remains high.

Hence a more attractive hypothesis to explain the contraceptive effect of breast feeding is that neural inputs from the nipple reach the hypothalamus. There they have the effect of stimulating the release of beta endorphin, which is thought to suppress the discharge of hypothalamic gonadotrophin-releasing hormone. The result is a decreased secretion of luteinizing hormone and therefore a failure of ovulation.

The same inputs from the nipple also inhibit the secretion of dopamine from the hypothalamus, and since dopamine normally holds the secretion of prolactin in check, the secretion of prolactin rises immediately. Thus the level of prolactin is a useful index of the degree of hypothalamic inhibition caused by suckling, but it may be quite unrelated to the cause of the ovulatory inhibition.

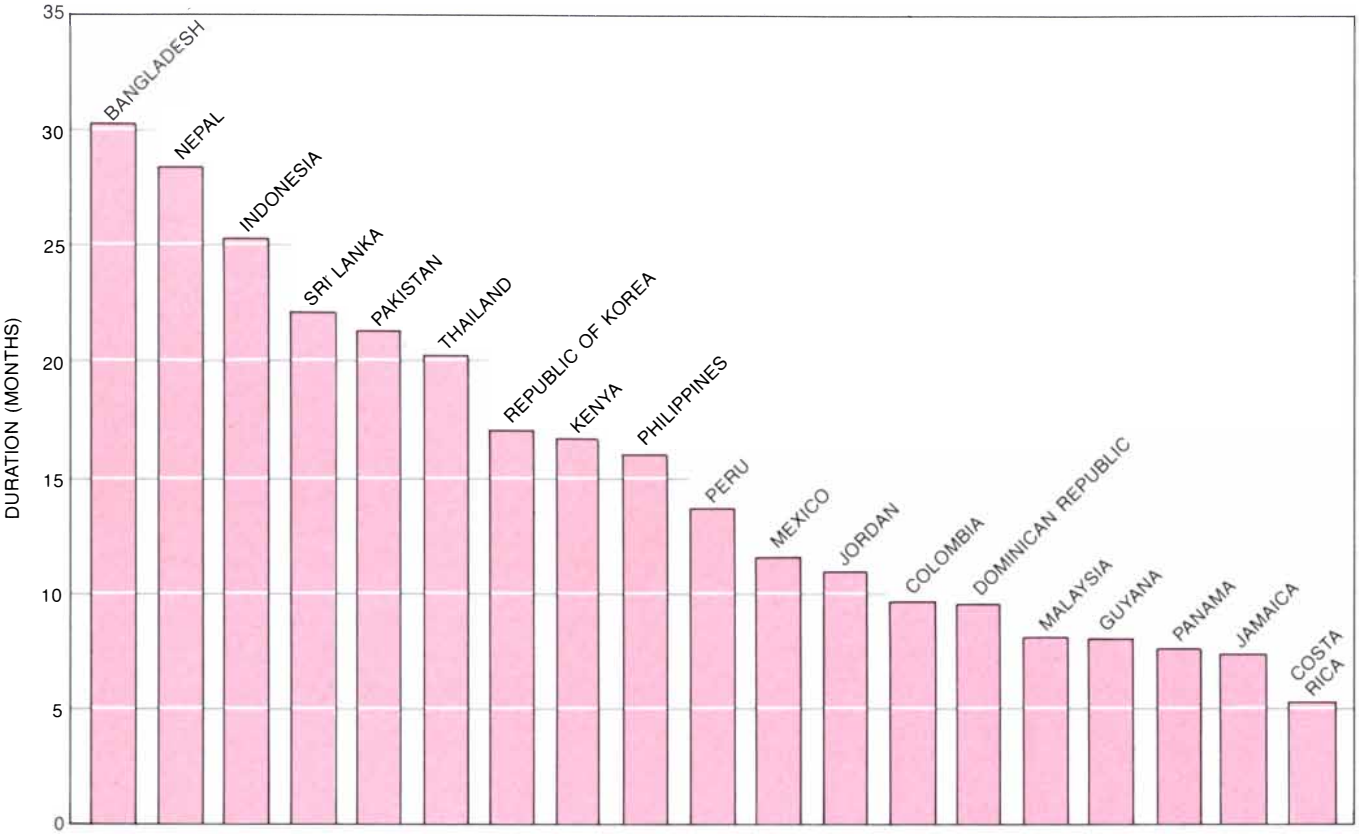
Since the suckling stimulus is evidently the crucial factor in causing the contraceptive effect, one should examine suckling behavior in some detail in order to understand what is happening. Peter W. Howie and Alan S. McNeilly, my former colleagues in the Medical Research Council unit in Edinburgh, studied 27 breast-feeding Scottish women throughout the period of their lactation, monitoring ovarian activity by measurements of estrogen and pregnan-



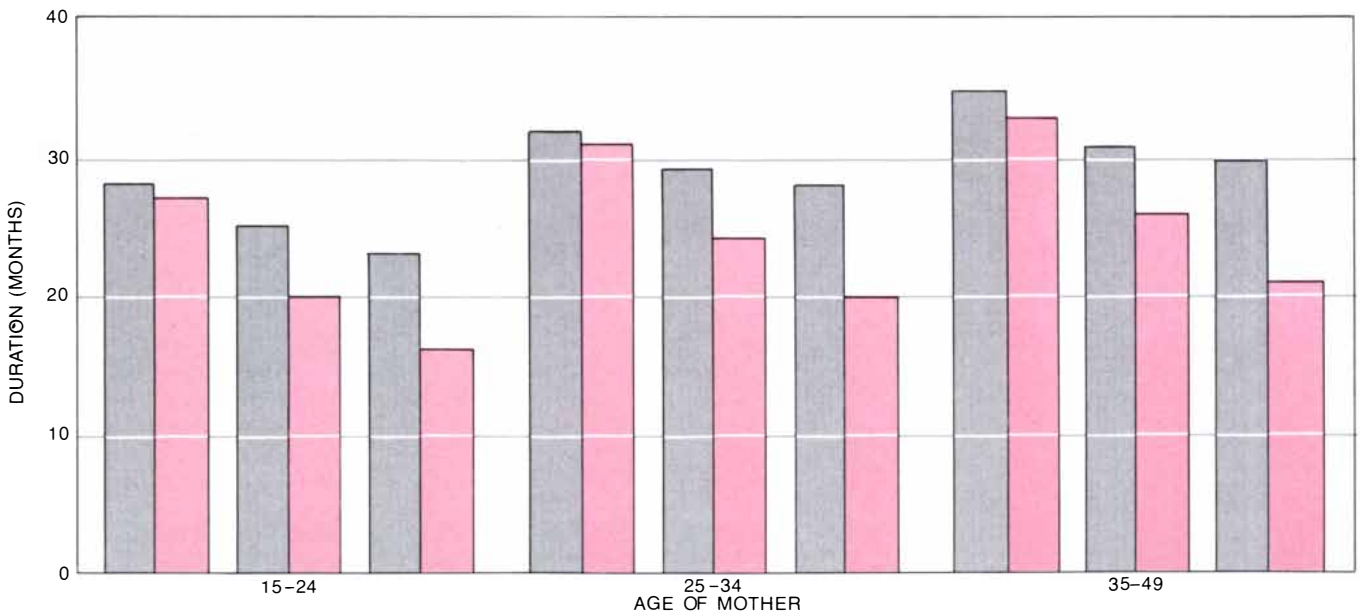
BIRTH INTERVALS for three types of breast feeding in the absence of contraceptives are charted. Women of the !Kung hunter-gatherer people in Africa (*a*) nurse their babies frequently for three or four years, achieving a mean birth interval of 4.1 years and a mean of 4.7 live births during a woman's reproductive life. The Hutterites of North America (*b*), who nurse on a rigid schedule, start giving the infant supplemental food a few months after birth and wean it within a year, have a mean birth interval of two years and a mean of 10.6 live births. A woman in the United Kingdom (*c*) who never nursed her babies and whose lactation was suppressed with stilbestrol or ethinyl estradiol after each delivery had a mean birth interval of 1.3 years.

ediol in the urine while keeping careful records of the time and duration of each feeding. As a control they also followed 10 women who had decided to bottle-feed their baby from birth.

The findings were most interesting. Whereas the bottle-feeding women began to menstruate an average of eight weeks after delivery and to ovulate after 11 weeks, the breast-feeding mothers began to menstruate an average of 33 weeks after delivery and to ovulate 36 weeks after delivery. No woman ovulated if she was breast feeding six or more times a day and for more than 60 minutes a day, and no woman ovulated during unsupplemented breast feeding. When the women were grouped according to whether they ovulated late (more than 40 weeks after delivery) or early (less than 30 weeks), it could be seen



DURATION OF BREAST FEEDING in a selection of developing countries shows a considerable variation. The position plotted for each country is a mean; in general the younger mothers (aged 15 to 24) nursed for a shorter time than women in the age groups of 25–34 and 35–49. The data were assembled in 1980 in the World Fertility Survey, directed by the International Statistical Institute in London.



RURAL AND URBAN MOTHERS in Bangladesh differ in the length of time they spend breast feeding. In each pair of bars the rural mothers are represented by gray and the urban mothers by color. In each set of three pairs of bars per age group the pair at the left represents women with no schooling, the middle pair women with a primary school education and the pair at the right women who completed secondary school. In a number of developing countries young, urban, educated women tend to abandon or shorten breast feeding.

that the late-ovulating group breast-fed longer (mean duration of lactation 53 weeks), suckled oftener, kept up nighttime feeding longer and introduced supplementary foods for the baby more gradually. When supplements were introduced, at about 16 weeks after delivery, there was a sharp decline in the frequency of suckling and in the level of prolactin in the blood. Within 16 weeks of introducing supplements ovarian follicles had begun to develop in 20 of the 27 women and 14 of them had ovulated.

James B. Brown of the University of Melbourne has done a larger study on 55 breast-feeding women. They tended to breast-feed longer than the Edinburgh women. Brown was not able to ascertain suckling behavior in quite as much detail. By combining the results of the Edinburgh and Melbourne studies one can begin to draw some general conclusions about the resumption of fertility following childbirth.

In the great majority of breast-feeding women the ovaries are inactive for most of the period of lactational amenorrhea. With increasing time after birth, as supplements are gradually introduced into the baby's diet, the frequency and duration of suckling start to decline and cyclical ovarian activity resumes. Thus most breast-feeding women will eventually start to menstruate and ovulate while they are still lactating. The pattern explains the popularly held belief that breast feeding is an unreliable form of contraception.

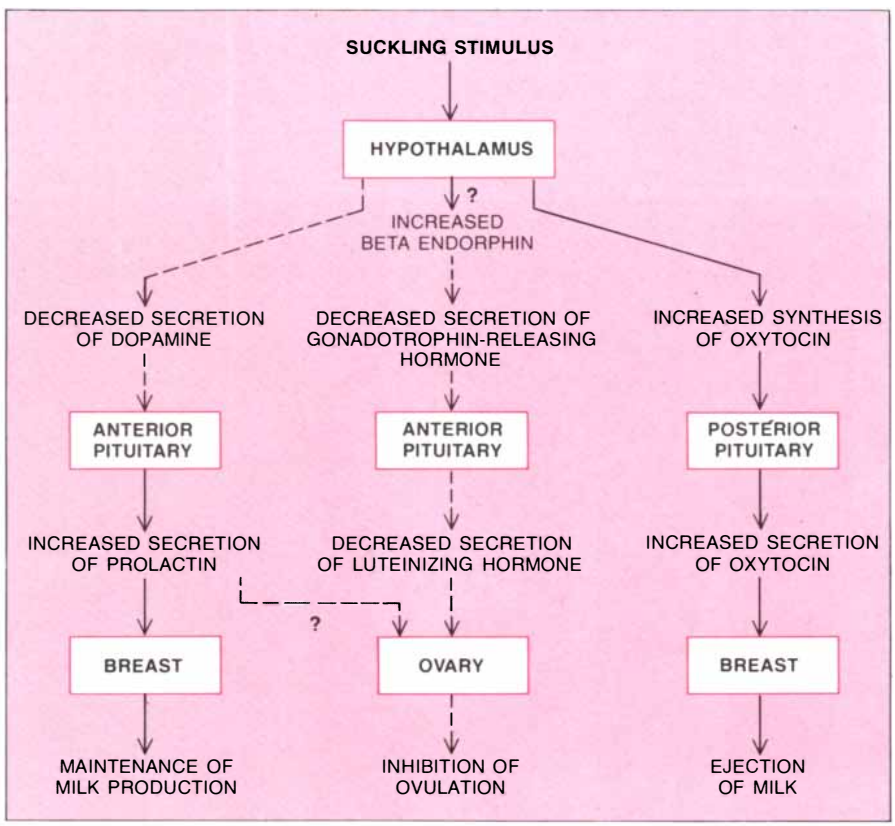
A look at the endocrine events preceding this first menstruation following delivery in the Edinburgh and Melbourne studies reveals, however, that in the majority of cases (58 percent) the woman failed to ovulate before she menstruated. Menstruation presumably was the result of the degeneration of a developing follicle in the ovary, causing a withdrawal of estrogen. When ovulation did precede the first menstruation, it was usually followed by a short or deficient luteal phase of the cycle. It seems unlikely that in those women the corpus luteum of the ovary could have supported a pregnancy even if an egg had been fertilized. In only 19 percent of the cases in the Melbourne study was there a normal ovulatory cycle preceding the first menstruation after the birth of the baby.

Since the maximum probability of conception in a normal menstrual cycle is only about 25 percent, the finding suggests that only 5 percent of the lactating women who resume unprotected intercourse before the first menstruation are likely to become pregnant. The figure is in good agreement with the observed incidence of conception (from 2 to 8 percent) during lactational amenorrhea in developing countries. Although to those who live in developed countries this rate of contraceptive failure during lactational amenorrhea might seem unacceptably high, it must be remembered that in the setting of a developing country the protection afforded by the best of modern contraceptives is no better because many women do not use the preparations properly.

A comparison of the Edinburgh and Melbourne women with the !Kung reveals several striking differences. Most of the former weaned their baby within 1.5 years, whereas the !Kung women continued to feed their baby for about 3.5 years. Few of the Edinburgh and Melbourne women fed their baby more than eight times in 24 hours; for the !Kung women the figure during the 12 hours of daylight was about 48. (The total time per day—between 100 and 150 minutes—was probably about the same for all the women.)

A particularly important difference may be that the Edinburgh and Melbourne women tended to give up nighttime feeding as soon as they could, whereas the !Kung women slept with their baby, so that nighttime feeding continued throughout lactation. It is known from experiments with cattle that the interval of time between feedings may be particularly important for the inhibition of postpartum ovulation. If calves are allowed to suckle for only 30 minutes a day, they grow at a normal rate but the cows return to estrus almost immediately. If calves are allowed to suckle at will, the cows have a prolonged period of lactational inhibition of estrus. Hence the abandonment of nighttime feeding by many women may allow the hypothalamus to escape from the suckling inhibition, so that the activity of the ovaries resumes.

Some people have sought to explain prolonged periods of lactational amenorrhea as an effect of undernutrition. That argument would certainly not apply to the Edinburgh and Melbourne women, who were all well nourished. John Bongaarts of the Population Council has reviewed the evidence from a number of developing countries and has concluded that moderate degrees of chronic malnutrition have only a minor effect on the duration of lactational amenorrhea. There may be, however, a subtle interaction of the level of nutrition with the frequency of suckling. Andrew S. Loudon of the University of Edinburgh, working with red deer in Scot-



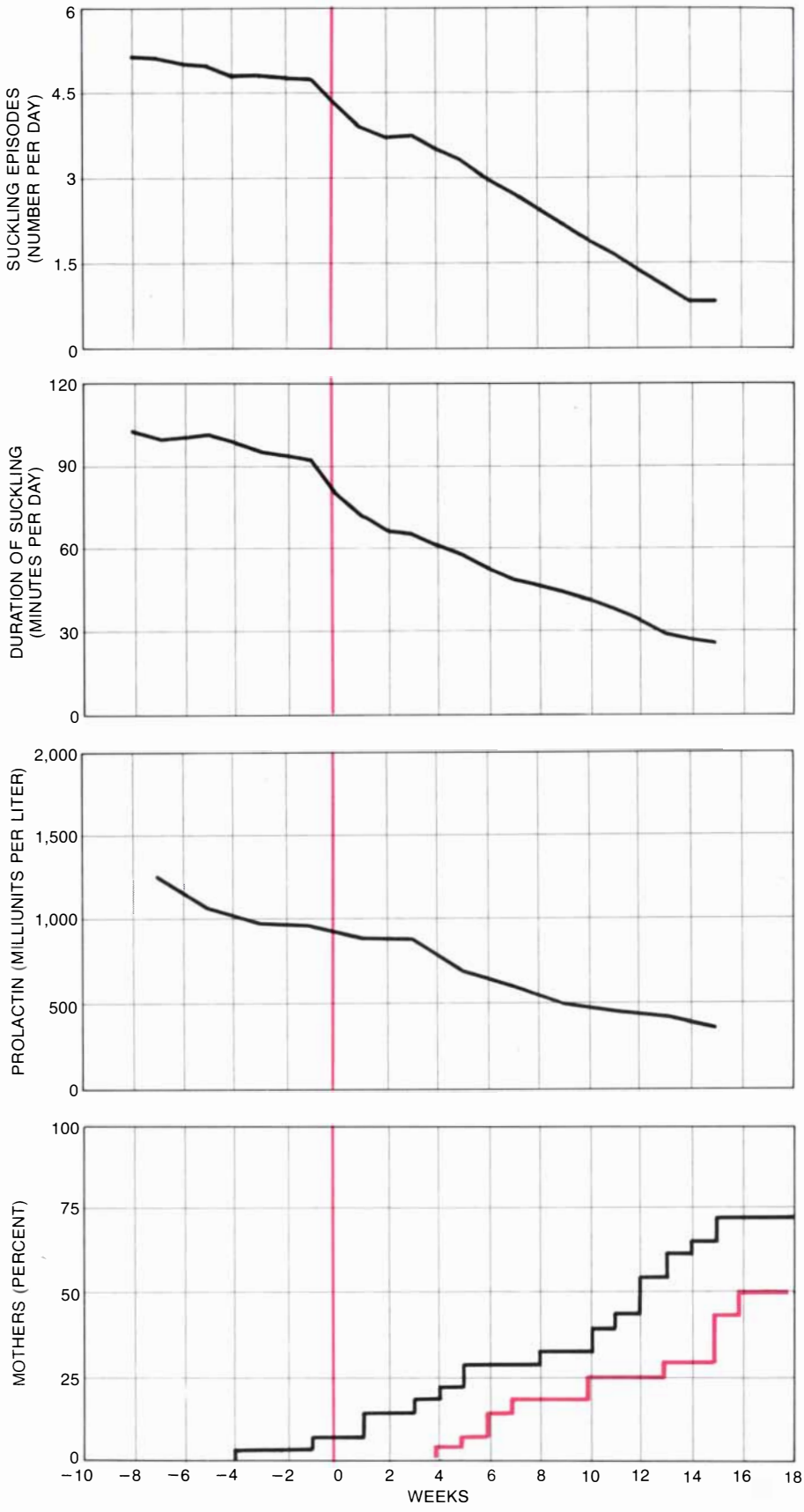
HORMONAL EFFECTS of breast feeding are set in motion by the stimulus of suckling. Here some of the hormones made by the hypothalamus and the pituitary gland are identified. When the effect of a hormone is to stimulate or increase a process, the effect is represented by a solid arrow. The inhibition of a hormone or a process is represented by a broken arrow. Since the secretion of prolactin by the pituitary is normally inhibited by the secretion of dopamine by the hypothalamus, lowering the level of dopamine increases the secretion of prolactin. Oxytocin is synthesized by the hypothalamus and passed down nerve fibers to the posterior pituitary gland from which it is released into the circulatory system of the body, aiding the ejection of milk.

land, has shown that hinds on poor hill grazings produced much less milk than those on permanent grass pastures. As a result the undernourished calves suckled much oftener and their dams had higher levels of prolactin and returned to estrus later than those at pasture.

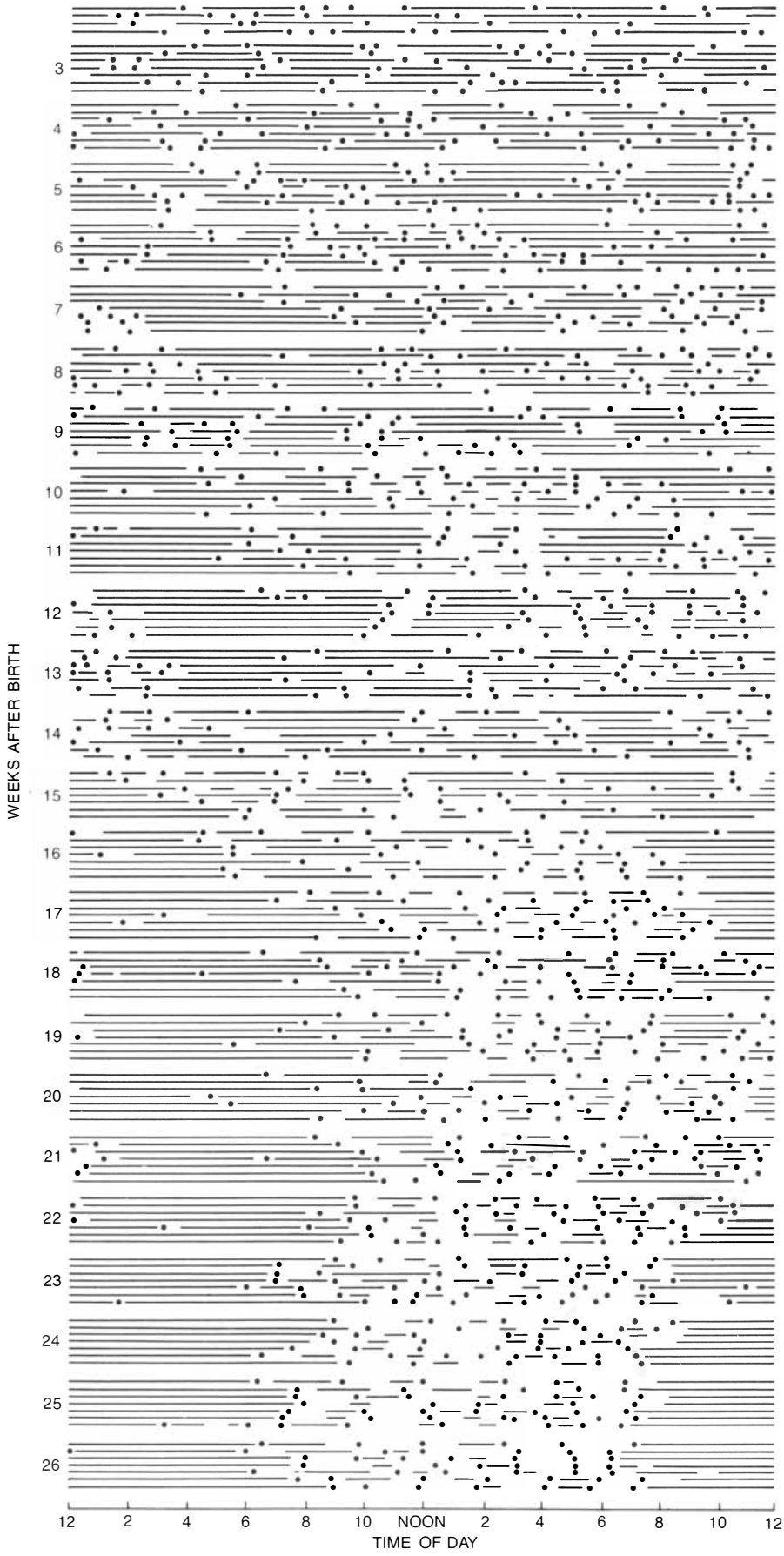
Roger G. Whitehead and his colleagues of the Dunn Nutrition Unit of the Medical Research Council in Cambridge have done studies in the Republic of the Gambia in which malnourished lactating women were given supplemental food (700 kilocalories per day) in the form of a high-energy biscuit. Whitehead concluded that the yield of milk was not increased, although levels of prolactin fell and ovulation resumed sooner than they did in the unsupplemented controls. Taken at face value, this evidence would suggest that if a mother who is breast feeding is severely malnourished, her baby's diet will require independent supplementation, since feeding the mother will not increase her yield of milk.

Surely the suggestion is wrong. Any dairy farmer who believed the level of nutrition has no effect on the cow's yield of milk would soon go out of business. In the light of the results with red deer it seems more probable that the dietary supplementation did increase the yield of milk in the Gambian women and that the increase was reflected in a decreased frequency of suckling. (The frequency of suckling was not accurately recorded in the study.) The result was a drop in the prolactin level and an early return to ovulation. Given the choice of supplementing either the diet of the mother alone or the diets of the mother and infant independently, the former would clearly be preferable. It not only would enable the mother to manufacture more of the ideal food for her baby but also would preserve at least some of the contraceptive effect of suckling. Further information on how supplemental feeding affects the yield of milk is urgently needed, since it should constitute the philosophical base of aid to starving populations in developing countries.

When should supplemental food be added to the baby's diet? One approach to the question has been to establish "normal" infant-growth curves (almost invariably compiled from infants who have been bottle-fed on a schedule with a formula based on cow's milk or pasteurized human milk) and to determine when the growth rate of the breast-fed baby starts to depart from this norm. An alternative method has been to estimate the yield of milk by lactating women and to calculate the energy demands of the growing infant and the caloric value of human milk. With such an approach John C. Waterlow of the London School of Hygiene and Tropical Medicine recently concluded that exclusive



SUPPLEMENTAL FOOD given to a breast-feeding infant from three to 24 weeks after birth has a number of effects. Here the results are centered around the time of introduction of supplements, represented by the vertical colored line. The effects shown are, from the top, on the number of times per day a baby nurses, on the baby's total suckling time per day, on the level of the hormone prolactin in the mother's circulatory system and on her ovaries, as represented by the percentage of women showing an increase in the synthesis of estrogen by the ovaries (*black*) and ovulating (*color*). The data are based on a study of 27 mothers in Edinburgh.



FEEDING CYCLES of a suckling infant are traced from the 11th to the 182nd day of life. The solid lines represent periods of sleep, the dots represent feedings and the open spaces represent periods of wakefulness. It is evident that the mother has gradually trained the baby to abandon nighttime suckling, thereby eroding the contraceptive effect of breast feeding.

breast feeding would fail to satisfy the energy needs of many infants after about three months. On the other hand, Chung H. Ahn and William C. MacLean of the Johns Hopkins University School of Medicine have shown that babies (of mothers taking part in the La Lèche program) who were exclusively breast-fed for from six to 12 months grew perfectly normally, at least for the first nine or 10 months.

Another way of determining when supplements are needed is to look in the baby's mouth. The time when teeth emerge was surely established in the course of evolution to provide the baby with an alternative means of feeding itself at the appropriate stage of development. The hunter-gatherers had no access to specialized baby foods; the infant had to be weaned directly onto the diet of adults, which required chewing. Since the incisors do not appear until about six months after birth and there are no occlusable teeth until nine or 10 months, one can argue that this is the natural time to start supplemental feeding.

One clear mistake is a gross underestimate of the potential yield of human milk. The generally accepted figure is 700 milliliters per day when the infant is six weeks old, rising to about 800 milliliters from the baby's third month of life onward. Peter E. Hartmann of the University of Western Australia has shown, however, that Australian women who feed their babies breast milk only, on demand, for up to 15 months can readily produce 1,500 milliliters per day. With twins the yield can be more than 2,500 milliliters. The mammary gland is thus a splendid supply-and-demand organ: the oftener milk is removed from it, the more milk it will secrete. The phenomenon is probably the result of an intra-alveolar mechanism whereby a distention of the alveolus caused by the presence of milk inhibits the further synthesis of milk, although the precise mechanism is not understood.

In many countries, both developing and developed, it is common for the mother to start feeding the baby supplements quite early, sometimes from the day of birth. This practice can only serve to diminish the supply of breast milk, to expose the baby to an unnecessary risk of infection and to undermine the contraceptive effect of breast feeding. There is also some new evidence showing that the introduction of supplements in the first four months of life may lead to the development of childhood eczema. It would be far more sensible to encourage the mother to feed her baby exclusively on breast milk, at least for the first six months, and to supplement her own diet rather than the baby's during that time.

Another current controversy relates to the type of contraceptive a lactating mother should use and the time for

her to start using it. In developed countries, where women usually breast-feed for a relatively short period of time and where they take for granted the availability of an almost foolproof method of contraception, the practice has been to advocate barrier methods, an intrauterine device or the progestin-only minipill within about a month of delivery. (The standard contraceptive pill contains a combination of estrogen and progestin; the estrogen is withheld in the minipill because it inhibits lactation.)

In developing countries, where women breast-feed much longer and where both contraceptive services and the use of them are poor, the situation is entirely different. As I have pointed out, the contraceptive protection afforded by lactational amenorrhea is at least as good as that of any modern contraceptive. Since lactational amenorrhea may last for a year or more, there seems to be little reason for "double cover" during that time. Indeed, a study in Bangladesh has suggested that the introduction of the two-hormone contraceptive pill to lactating women may actually enhance their fertility, since its depressant effect on the yield of milk probably hastens weaning. By the time of weaning a number of women will already have forsaken the pill, thereby losing all protection against pregnancy.

One of the most effective and safest contraceptives for lactating women in developing countries and the simplest to administer is Depo-Provera. It is a progestin given by injection once every three months, during which time it suppresses ovulation and menstruation. Ideally it should be administered late in lactation, just before menstruation is expected to resume.

I touch here on an area of controversy. Studies by the WHO have as yet failed to identify any health risk associated with the use of Depo-Provera and have shown no adverse effect on the composition or yield of breast milk. On the other hand, many authorities in developed countries oppose this use of Depo-Provera because it has not yet been conclusively shown to have no adverse side effects. For example, if a woman conceived during lactation even though she had received Depo-Provera, there is reason to believe the risk of birth defects would increase. Because of opposition from consumer groups, the U.S. Food and Drug Administration has reversed a decision it once reached to approve the drug for contraceptive use in the U.S.; the case is on appeal. Hence Depo-Provera cannot be part of family-planning programs funded by the U.S. Agency for International Development.

The British Minister of Health overruled, for unspecified "nonmedical reasons," the advice of his Committee on the Safety of Medicines and refused to approve Depo-Provera as a contraceptive. The Swedish National Board of Health and Welfare has approved it as a contraceptive for use even by midwives within Sweden, but the Swedish International Development Authority has withdrawn all funds for distributing it internationally. The West German Federal Health Office recently approved Depo-Provera for lactating women, reversing an earlier decision that disallowed the drug because of "the threat of an unjustifiable health risk." The Australian Drug Evaluation Committee has banned Depo-Provera as a contraceptive for "lack of clinical data," in spite of the fact that an estimated 1.5 million women around the world are using it for contraception.

ANCIENT FEEDING VESSELS indicate that the trend away from breast feeding began long ago. These pottery vessels are in the collection of the Wellcome Institute for the History of Medicine in London. The one on the left is from Cyprus and dates from about the 10th century B.C.; the one on the right is from southern Italy and dates from the fourth or third century B.C. A small piece cut from a sponge may have been put in the spout to serve as a teat.

One of the reasons underlying this hesitancy relates to the unknown risk from the small amounts of progestin excreted in the mother's milk and absorbed by the infant. Yet bottle-fed infants who receive cow's milk or formulas based on it are also exposed to small amounts of steroids. The reason is that most lactating dairy cows are pregnant, and milk is one of the excretory pathways for the elevated levels of progesterone and estrone sulfate associated with gestation. Ironically, when a lactating woman becomes pregnant, her milk also contains progesterone and estrogen—a state of affairs that Depo-Provera is specifically designed to prevent. It would be better for all concerned if the regulatory agencies approved Depo-Provera as a contraceptive for lactating women and banned the feeding of all cow's-milk products to babies.

One reason a continuing supply of breast milk is vital for infant health in developing countries has to do with the passage of white blood cells from the intestines to the breast. This pathway was discovered only within the past decade. Peyer's patches (large masses of gut-associated lymphoid tissue adjacent to the small intestine) contain antigen-committed cells sensitized to the intestinal pathogens the mother has encountered during her life. If she ingests one of those pathogens during lactation, sensitized cells migrate from the Peyer's patches into the systemic circulation, where they proceed to her breasts and become plasma cells that release into her milk a specific immunoglobin *A* directed against the pathogen. The process may be facilitated by the high level of prolactin in the circulation.

During the fourth month of lactation a woman may be secreting as much as .5 gram of antibody into her milk per day. The antibody is not absorbed by the infant but remains in the gut, where it plays a vital role in preventing gastrointestinal infections (the main cause of infant mortality). No formula milk, however cunningly it is contrived, can replace this tailor-made immunological protection afforded by breast milk.

The steady decline of breast feeding is a major human tragedy. At one and the same time it has caused an excessive stimulation of maternal fertility and an enormous increase in infant mortality. More than enough is already known to prevent the repetition of the tragedy in developing countries. The challenge is to translate the knowledge into action.

Molecular Clouds, Star Formation and Galactic Structure

Radio observations show that the giant clouds of molecules where stars are born are distributed in various ways in spiral galaxies, perhaps accounting for the variation in their optical appearance

by Nick Scoville and Judith S. Young

Most of the stars visible in the night sky were formed more than a billion years ago. Star formation is a continuing process, however, and much of what is fascinating about the universe has to do in one way or another with the comparatively small number of much younger stars. The most massive, short-lived members of each stellar generation are of particular interest. In youth they energize the fluorescent nebulas that stud the spiral arms of galaxies such as our own. In death they explode spectacularly as supernovas, replenishing the interstellar environment with a mixture of gases, including an enriched fraction of heavy elements. It is from these ashes that future generations of stars will arise. In recent years it has become clear, mainly from observations made by means of radio telescopes, that the springs of this rejuvenation are giant molecular clouds, measuring more than 100 light-years across and encompassing a mass of gaseous material up to a million times the mass of the sun. Inside these immense cocoons the metamorphosis of stars takes place in cold and dusty darkness.

Although the giant gas clouds are known to be fertile sites for the formation of stars, it is significant that they have not been completely assimilated into stars. Today, more than 10 billion years after the birth of our galaxy, one can still see many young stars emerging from the clouds in which they were formed. Isolated from the galactic environment, the clouds would collapse under their own weight, transforming their diffuse gas into stars in less than 10 million years. If star formation were inevitable, requiring merely that an adequate mass of material be accumulated into a cloud, the supply of interstellar gas needed to form the next generation of stars would have dwindled long ago to insignificance. Thus a subtle interplay of the clouds and their galactic environment must effectively regulate the formation of stars. One of the most exciting episodes of contemporary astrophysics has been the observational and theoretical work done in an attempt to define the role of the giant molecular clouds in galactic evolution and to establish the links between star formation and the large-scale structure of galaxies.

The proportion of stars that are young can vary greatly both from galaxy to galaxy and from place to place in an individual galaxy. In spiral galaxies such as ours the arms appear fairly bright in photographs made in visible light, owing to the concentration of massive, young stars along their length. Although such stars have a comparatively brief lifetime (less than 10 million years), their rate of radiation can be a million times that of the sun. Hence their birthplaces will be brightly illuminated for a few million years. One of the most remarkable features of spiral galaxies, first recognized 40 years ago by Walter Baade of the Mount Wilson Observatory, is the apparent correlation in the positions of massive stars such that a grand spiral pattern is perceived. The bright arms can often be traced over a complete turn, spanning a distance of perhaps 200,000 light-years.

How is it that the formation of massive stars can be correlated over the entire galactic disk, a range well beyond the physical effects of one cloud on another or the sphere of influence of an individual star? There are now two schools of thought on the question. It was first proposed by Chia-Chiao Lin and Frank H. Shu of the Massachusetts Institute of Technology that these large-scale patterns are density waves generated by the collective gravitational interactions of billions of stars in the galactic system or by the tidal pull of a nearby galaxy. More recently Philip E. Seiden and Humberto C. Gerola of the IBM Thomas J. Watson Research Center have suggested as an alternative that star formation may spread across the face of a galaxy like a forest fire, with the formation of massive stars at one location setting off the formation of other stars in adjacent clouds. (A third possibility is that the clouds exist and form stars throughout the galactic disk, but that near the spiral arms their properties change and they preferentially form the more massive stars there.)

For years astronomers have been able to identify gas clouds near the solar system as sites of active star formation. Viewing the actual birth process, however, was not possible until recently. A small admixture of dust in the clouds, constituting about 1 percent of the mass, effectively absorbs the visible and ultraviolet radiation from embedded young stars in all but the most tenuous clouds. The microscopic dust particles are composed of carbon (in the form of graphite), silicates and other compounds similar to some terrestrial and lunar rocks. Although the dust in interstellar space is quite sparse, it is readily apparent when one gazes at the Milky Way on a dark night. One then sees the disk of our galaxy not as a single, smooth band of stars across the sky but as two bands, with a dark void between them. The rift appears because the light from more distant stars in the galaxy is absorbed by clouds of gas and dust lying in the foreground along the line of sight.

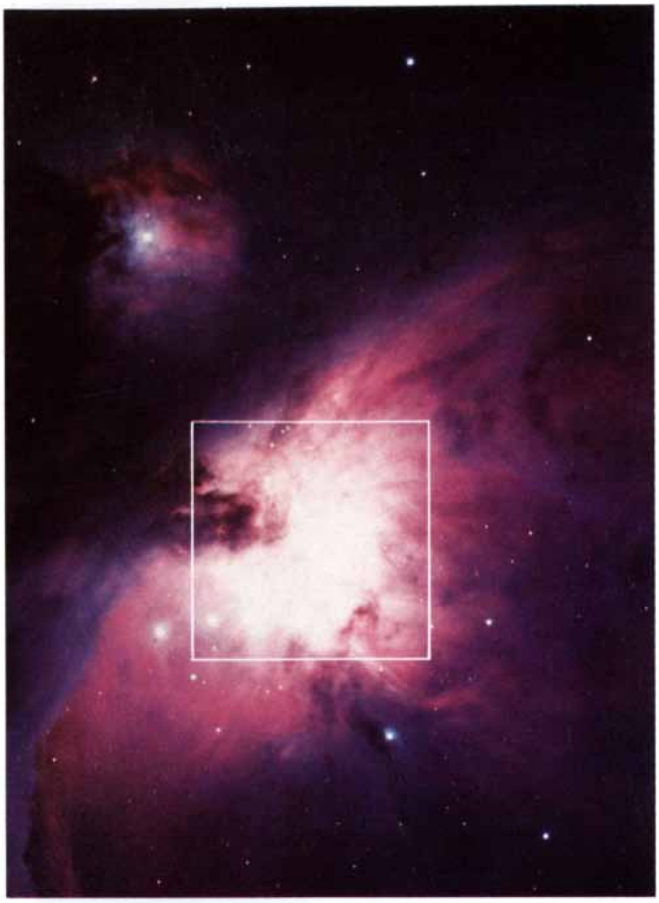
The layer of galactic dust seen silhouetted against the background stars has a thickness of 300 light-years. Because of the dust, it has been impossible to observe visually the very youngest stars until they either drift away from the enshrouding cloud or release enough energy to disperse it. As the stars age they interact gravitationally with the massive interstellar clouds, gradually increasing the distance by which they are flung outward from the galactic disk before they fall back. As a result, although most of the stars were probably formed out of gas clouds in the thin disk, the thickness

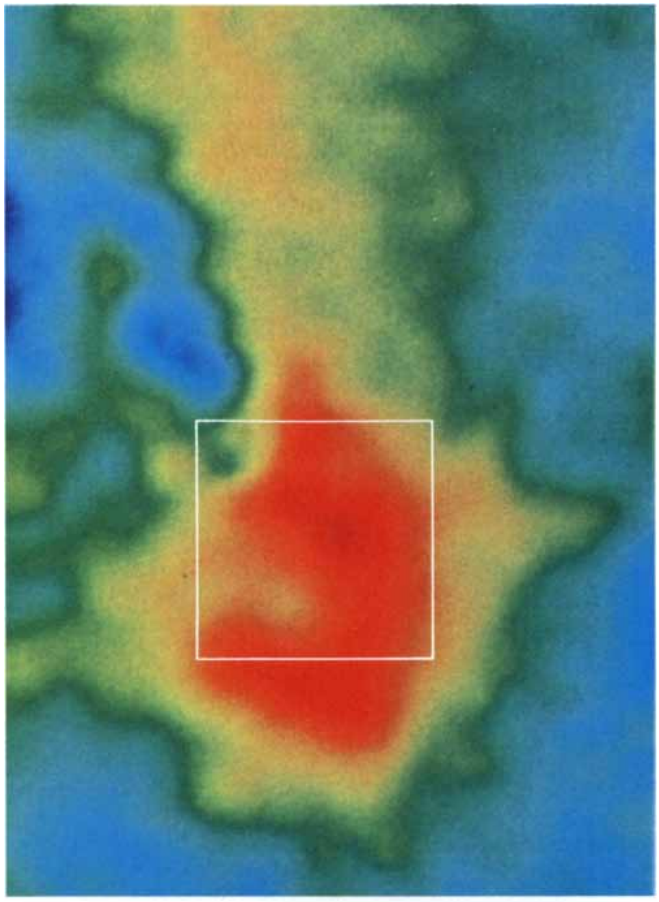
of the older stellar layer has increased to about 1,000 light-years.

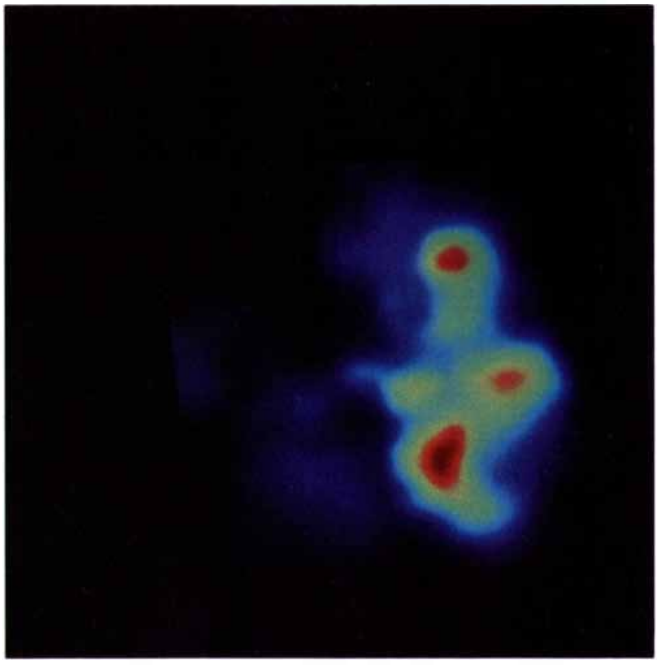
One of the best-known stellar nurseries in our galaxy is the Great Nebula in Orion. The luminous nebula is easy to see with binoculars in the middle of the dagger below Orion's Belt. Astronomers now recognize that the bright emission from the nebula, first studied more than a century ago, is a manifestation of the final phase in the process of star formation. Near the center of the nebula's emission is the Trapezium star cluster, which includes several massive young stars. The most massive of them radiates energy at a rate 100,000 times that of the sun. A substantial fraction of the radiation is in the ultraviolet region of the spectrum, and hence it is sufficiently energetic to strip electrons from atomic hydrogen, thereby ionizing the hydrogen in the surrounding gas. The bright visible emission, characteristically pink in color, is actually fluorescent light at a wavelength of 6,563 angstrom units emitted by the ionized hydrogen when it recombines, capturing a free electron.

For the entire nebula this cycle of ionization and recombination is repeated approximately 10^{50} times per second. Thus in spite of the fact that the region is some 1,700 light-years from the solar system, it is observed to glow brilliantly. In the nebular gas the ionization of hydrogen atoms proceeds about 1,000 times faster than the reverse process: the recombination of electrons and protons to form hydrogen atoms. Hence a state

SPIRAL GALAXY, designated M101 in the Messier catalogue of extended celestial objects, is seen almost face on in this photograph, made with the four-meter reflecting telescope at the Kitt Peak National Observatory. Estimated to be approximately 20 million light-years away, the galaxy has a span across the line of sight of about 300,000 light-years. The spiral arms are illuminated by bright ionized-hydrogen, or H II, regions, which are heated to fluorescence by massive young stars embedded in them. The dark filaments in the spiral arms are dust lanes. The comparatively small galactic nucleus and rather open arms make M101 a typical example of an *Sc* galaxy (*see illustration on page 48*). Radio observations of carbon monoxide (CO) molecules in the vicinity of M101 reveal that the star-forming molecular clouds there are concentrated toward the center of the galaxy, extending outward to a radius of roughly 40,000 light-years.







FOUR VIEWS OF THE ORION NEBULA are presented on this page. The photograph at the top left was made with the four-meter telescope on Kitt Peak. The computer-generated false-color image at the top right, covering the same region of the sky, was made from a record of the radio waves emitted by carbon monoxide molecules in the vicinity of the nebula; the CO data were collected with the 14-meter radio telescope of the Five College Radio Astronomy Observatory in Massachusetts. The photograph at the bottom left, made with the three-meter telescope at the Lick Observatory, gives a somewhat more detailed view of the central part of the nebula, which is outlined by the square in the two top views. The more detailed photograph, which was exposed through a filter that preferentially passes the green light emitted by singly ionized oxygen atoms, reveals the central group of luminous young stars, known collectively as the Trapezium cluster, that is responsible for the nebula's fluorescence. The corresponding image of the central region of the nebula at the bottom right was made with the National Aeronautics and Space Administration's infrared telescope on Mauna Kea in Hawaii. The bright spots in the infrared image represent the youngest stars in the nebula, which are still embedded in the central dust cloud and hence remain invisible. The infrared data were obtained by Gareth Wynn-Williams and Eric E. Becklin of the University of Hawaii, Reinhart Genzel of the University of California at Berkeley and Dennis Downes of the Institute for Millimeter-Wave Radioastronomy at Grenoble.

of ionization equilibrium exists in the nebula at a concentration of electrons and protons 1,000 times that of neutral (un-ionized) atomic hydrogen. Regions such as the Orion nebula, where the bulk of gas is ionized, are designated H II regions; they are the bright nebulas that delineate the spiral arms in galaxies.

As one of the nearest H II regions, the Orion nebula has become a Rosetta stone for studies of star formation and associated physical processes. Scanning the breadth of the visible nebula, one sees both stationary clumps and high-speed streams of plasma (ionized gas). Moving farther out from the Trapezium cluster, eventually one reaches the point where all the ultraviolet photons emitted by the four Trapezium stars have been exhausted in ionizing the gas. Beyond this radius the hydrogen can no longer be kept ionized. Until recently the ionized-hydrogen region was the only part of the nebula that could be observed. Strong obscuration by the grains of dust mixed with the neutral gas made it impossible to see inside the cloud.

Now developments in infrared astronomy and millimeter-wave radio astronomy have shown that the earlier observations at visible wavelengths were revealing little more than the tip of the iceberg. Both the infrared radiation and the millimeter-wave radiation are much less attenuated by the dust. The former makes it possible to detect stars deeply embedded in the dust; the latter provides a means of observing the molecular gas. The infrared data are in a sense a negative of the optical picture, since the dust that absorbs the visual light will subsequently reradiate the excess energy at infrared wavelengths. Thus in the infrared part of the spectrum one sees bright emission associated with luminous stars embedded in the dust cloud; one rarely sees the star itself but rather the reradiated energy from the heated dust nearby. Infrared observations of the Orion nebula have revealed two clusters of young stars deep in the neutral cloud. The fact that neither of the new clusters was even faintly apparent in visible-light photographs of the region is remarkable, inasmuch as one of the clusters is apparently emitting energy in the form of infrared radiation at a rate nearly identical with that of the Trapezium cluster, or 100,000 times the rate of the sun.

Inside the cloud behind the Orion nebula the gas is sufficiently dense and the temperature sufficiently low for most of the atoms to have become bound as molecules. Here, where the average temperature is lower than 100 degrees Kelvin (degrees Celsius above absolute zero), the most abundant constituent is molecular hydrogen (H_2). There are also numerous trace molecules such as carbon monoxide (CO), cyanogen (CN) and ammonia (NH_3). At the temperatures generally prevailing in the clouds the molecular hydrogen is not directly observable. Studies of the cool gas have relied on the trace molecules; unlike H_2, they can emit and absorb radiation at short radio wavelengths and in the far-infrared part of the spectrum. An important phase in the understanding of star-forming clouds was ushered in 15 years ago when Robert W. Wilson, Keith B. Jefferts and Arno A. Penzias of Bell Laboratories first detected carbon monoxide emission in the Orion cloud. Since then about 60 molecules ranging in complexity up to cyanopentacetylene ($HC_{11}N$) have been identified in such regions. The list includes formic acid (HCOOH), formaldehyde (H_2CO) and ethanol (C_2H_6O). Because the more complex molecules are not as abundant as CO, they can usually be detected only in the compact core of the clouds, where the gas is densest.

Carbon monoxide remains the best tracer of molecular gas over wide areas. In the Milky Way the mean density of interstellar matter is approximately one atom per cubic centimeter. The molecular clouds, which are the comparatively dense parts of the interstellar medium, have typical densities of from several hundred to several thousand molecules per cubic centimeter—still only a billionth of a billionth the density of the earth's atmosphere at sea level. Within the clouds carbon monoxide accounts for approximately one molecule for every 10,000 hydrogen molecules.

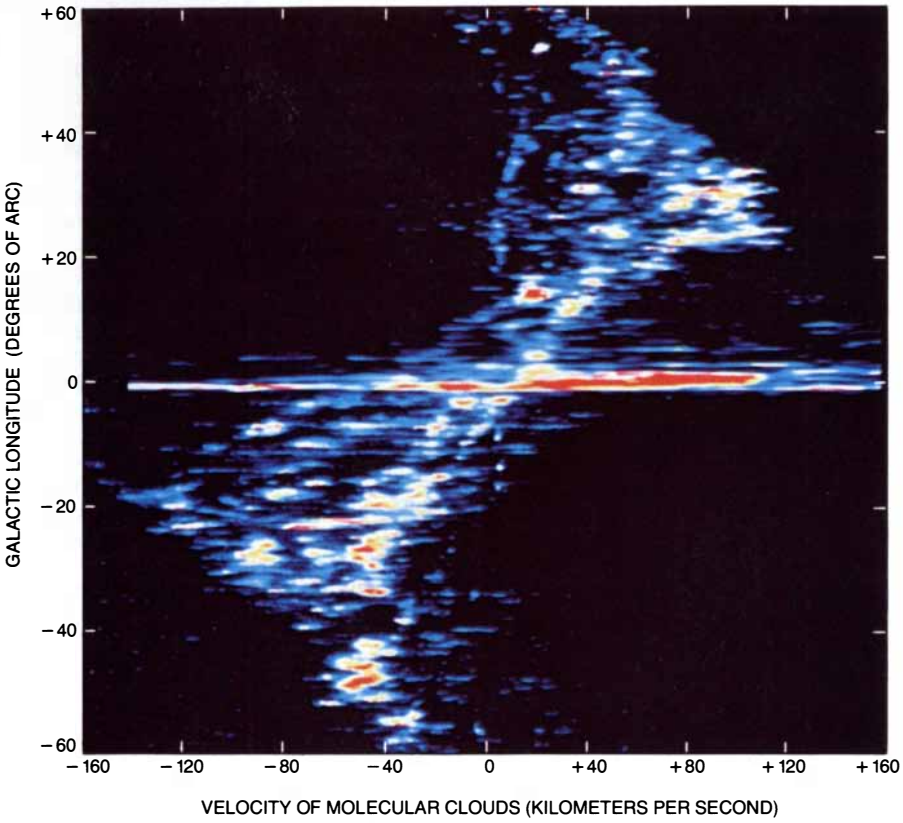
The binding of a molecule such as carbon monoxide results from the fact that the outermost electrons of the carbon and oxygen atoms are shared; each of the electrons spends some time near the other atom. Since the sharing is not exactly equal, there is a small net positive charge at one end of the molecule and a similar negative charge at the other end. It is the attraction between the opposite charges that keeps the atoms bound together.

The radiation detected from molecules in the interstellar clouds arises from changes in the rotation of the molecule as a whole; the permissible rotations are quantized rather than continuous. When the carbon monoxide molecule changes from a higher rate of rotation to a lower one, it radiates a photon, or quantum of electromagnetic radiation, with an energy equal to the reduction in the rotational energy. A transition from the first excited energy state of carbon monoxide to the ground state gives rise to a photon with a wavelength of 2.6 millimeters, corresponding to a radio frequency of 115,000 megahertz. Since each molecular species has a slightly different structure, each will radiate at a unique set of frequencies. Their spectral fingerprints are distinct and identifiable in the comparatively short millimeter-wave band.

Opening up this spectral band to astronomical observation has called for large technical investments at the National Radio Astronomy Observatory, Bell Laboratories and several universities where sensitive radio receivers and telescopes with sufficiently accurate reflecting surfaces have been built. Although the technology at short radio wavelengths was initially very taxing, there is a side benefit: even a modest-size telescope provides excellent angular resolution. A 14-meter telescope observing the 2.6-millimeter carbon monoxide line has a resolution of 50 seconds of arc. To obtain equivalent resolution observing the standard 21-centimeter line of atomic hydrogen would require a telescope nearly a mile in diameter.

From the carbon monoxide emission observed in a molecular cloud one can infer not only the density and the temperature of the molecules but also their motions. Motions of the gas along the line of sight are detected by measuring the Doppler shift in the frequency of the emission in a particular parcel of gas away from the frequency of the transition as it is measured in laboratories on the earth. The density and the temperature are inferred less directly. In the absence of external effects the molecule will radiate and decay into the state with the lowest rotational energy, and it will remain there until the environment supplies enough energy to reexcite it. The most important agency for this excitation is collisions with molecular hydrogen. Since the frequency of collision depends on the density of the molecules, the brightness of the molecular emission in a cloud serves as a measure of the density of molecular hydrogen. With carbon monoxide the radiative decays are sufficiently slow compared with typical collision times for the distribution of CO among the various rotational states to have a characteristic thermal distribution in all clouds except those of the lowest density. Hence in the denser clouds the brightness of the CO emission yields an estimate of the temperature in the molecular hydrogen. In such regions one must rely on other molecules, such as HCN (hydrogen cyanide) or CS (carbon monosulfide), which have a faster radiative decay, in order to measure the density of the gas.

The extent of the molecular cloud in Orion can be traced in carbon monoxide emission more than three degrees to the south and two degrees to the north of the bright optical H II region. This angular measurement corresponds to a linear distance of almost 100 light-years in the long dimension. Thus the linear extent of the molecular cloud is about 50 times larger than that of the optically bright region. The quantity of molecular gas



MOLECULAR CLOUDS IN OUR GALAXY were surveyed by means of the 2.6-millimeter radio waves emitted by carbon monoxide molecules in the inner disk of the galaxy. The individual gas clouds represented by the colored streaks are estimated to be between 50 and 200 light-years in diameter. This first complete survey of the interior part of the galaxy was compiled from a series of measurements made along the galactic plane with the 14-meter radio telescope in Massachusetts and a four-meter radio telescope operated by the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia. The vertical scale gives the galactic longitude in degrees of arc; zero corresponds to the direction of the center of the galaxy. The horizontal scale measures the velocity of the individual molecular clouds, on the basis of the Doppler shift in the frequency of the radio waves they emit from a standard frequency for carbon monoxide emission measured in the laboratory. Since the observed velocities are attributable mainly to the oribital motion of the clouds around the galactic center, the measurements serve as an indicator of the location of the clouds in the galaxy. The clouds are concentrated primarily at two places: at galactic longitudes lower than four degrees (corresponding to the central 2,000 light-years of the galaxy) and at both positive and negative longitudes between 20 and 40 degrees (corresponding to a ring of material midway between the sun and the galactic center). The survey was done by Daniel Clemens, David B. Sanders and one of the authors (Scoville) of the University of Massachusetts at Amherst, Philip M. Solomon of the State University of New York at Stony Brook, Richard N. Manchester, Brian Robinson and John Whiteoak of the CSIRO and William H. McCutcheon of the University of British Columbia. The processing of the color image was done at the University of Massachusetts Remote Sensing Center.

in this space is now estimated to be 200,000 times the mass of the sun, or about 1,000 times more than the total mass of the stars visible in the Trapezium cluster.

In the vicinity of the brightest infrared source in the nebula the situation is not at all what one would expect for the gradual collapse of a cold cloud in the process of forming stars. Within about five light-years of the embedded infrared sources their effects are clearly seen. Their radiation heats the surrounding dust, which in turn heats the molecular hydrogen. The carbon monoxide observations show a temperature gradient running from 20 degrees K. at a radius of five light-years to approximately 100 degrees at a radius of .1 light-year. Within .1 light-year an abrupt change appears: gas is moving supersonically (at speeds of up to Mach 100), and a small fraction of the molecular hydrogen is heated to more than 2,000 degrees. Although the cause of this phenomenon is not understood in any detail, it is generally believed that the motions are generated by an energetic young star shredding the last remnants of its natal cocoon. The high temperatures would be at shock fronts where the supersonic gas, thrown outward by the young star, collides with the surrounding cloud. By occasionally stirring up and disrupting the surrounding cloud such flows may account for the generally low rate of star formation in the clouds. Perhaps the birth of sufficiently energetic stars can effectively limit subsequent star formation in the same area.

The Orion cloud is just one of many such regions in our galaxy. To determine the quantity of molecular gas in the interior of the galaxy one of us (Scoville), working in collaboration with Philip M. Solomon of the State University of New York at Stony Brook, conducted in 1975 the first sampling of carbon monoxide emission from the galactic disk, using the 11-meter telescope of the National Radio Astronomy Observatory. The results bore little similarity to earlier pictures of the more tenuous atomic-hydrogen clouds, designated H I regions. The molecular clouds were found to be extremely plentiful in the central 500 to 1,000 light-years out from the galactic nucleus, but their number fell off at larger radii. Most surprising was the discovery that the density of the molecular gas rose again to a second peak at a radius about midway from the sun to the galactic center. This ring of molecular gas, with a peak at about 15,000 light-years from the center of the galaxy, also appeared in later, more complete surveys of carbon monoxide emission by radio astronomers at other observatories in the U.S.

Since all the early galactic data were collected with radio telescopes in the Northern Hemisphere, a question lingered about the extent to which the southern galactic plane shows a similar structure. Within the past year a group of radio astronomers led by Brian Robinson of the Commonwealth Scientific and Industrial Research Organization (CSIRO) in Australia has completed a study of the emission from carbon monoxide in the Southern Hemisphere. The amounts of molecular gas seen in equivalent areas on both the north and the south side of the galaxy agree to within 20 percent. The southern distribution is similar to the northern one in exhibiting a ring-shaped peak midway between the sun and the galactic center, but the detailed shape of the southern part of the ring is somewhat different: the peak is 30 percent lower in density and the width is correspondingly greater.

The total mass of molecular gas estimated from the carbon monoxide emission in the interior of our galaxy is between one billion and three billion solar masses, which is equivalent to about 15 percent of the total stellar mass in the same region. This amount of gas greatly exceeds the mass of interstellar atomic gas in the region and in fact is comparable to the amount of atomic hydrogen over the entire galaxy out to twice the sun's radius. It should be remembered that until a decade ago this major component in our galaxy was totally unobserved on a galactic scale. It is significant not only for its comparative abundance but also for the fact that the molecular-

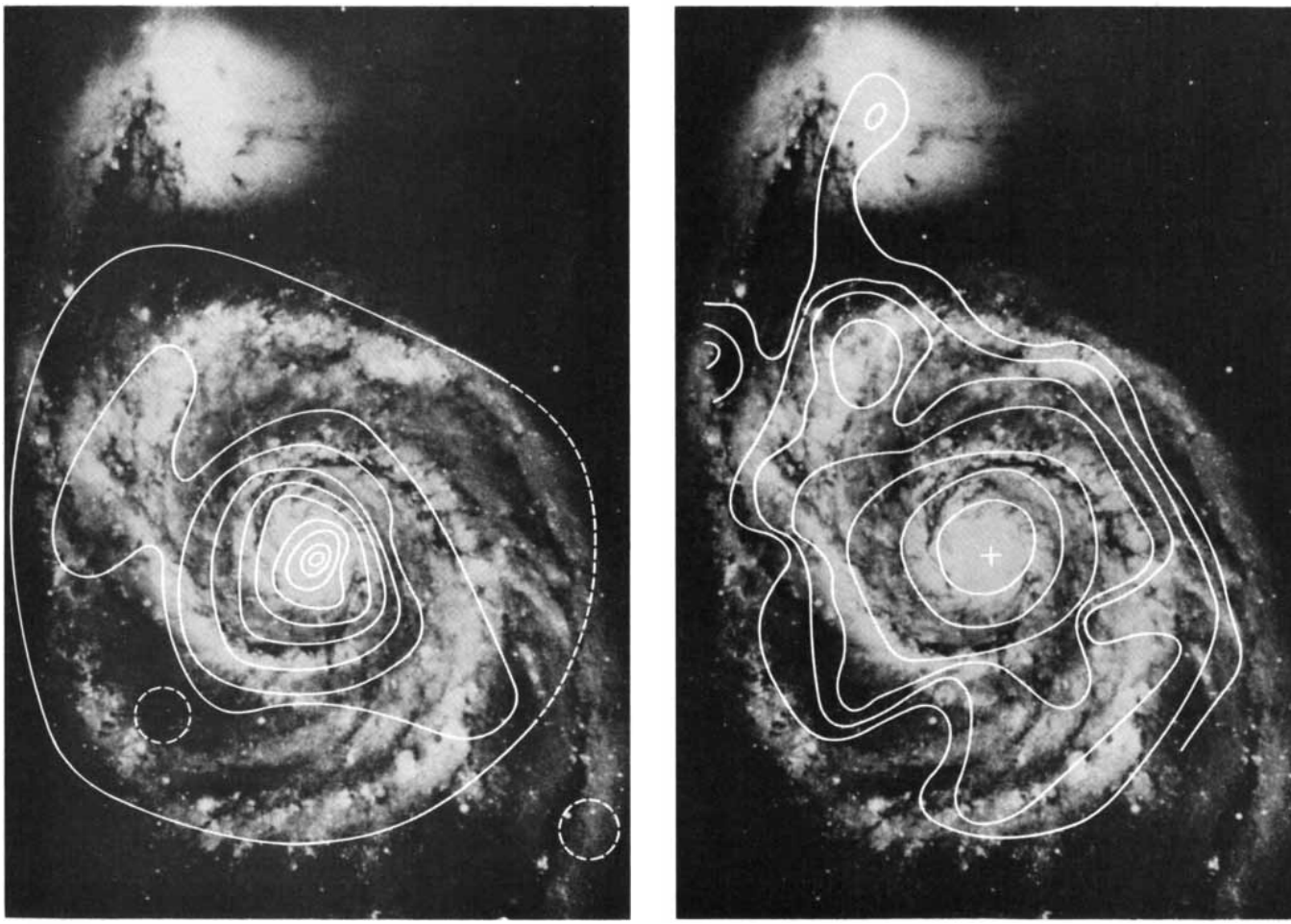
hydrogen clouds, not the atomic-hydrogen clouds, are the medium from which new stars arise.

Most remarkable are the properties of the molecular clouds. Far from being abnormally large, the Orion cloud is at the small end of the range of the giant molecular clouds in the galaxy. In 1981 David B. Sanders, then a graduate student at Stony Brook, measured more than 300 of the clouds in the galactic ring. He found that most of the gas was contained in clouds with a mean diameter of about 100 light-years. Although the clouds are extremely tenuous (about 300 hydrogen molecules per cubic centimeter), their volume is so great that their total mass amounts to between 100,000 and several million times that of the sun. Indeed, the giant molecular clouds are now thought to be the most massive objects in the galaxy. The number of clouds larger than 50 light-years in diameter is probably about 5,000.

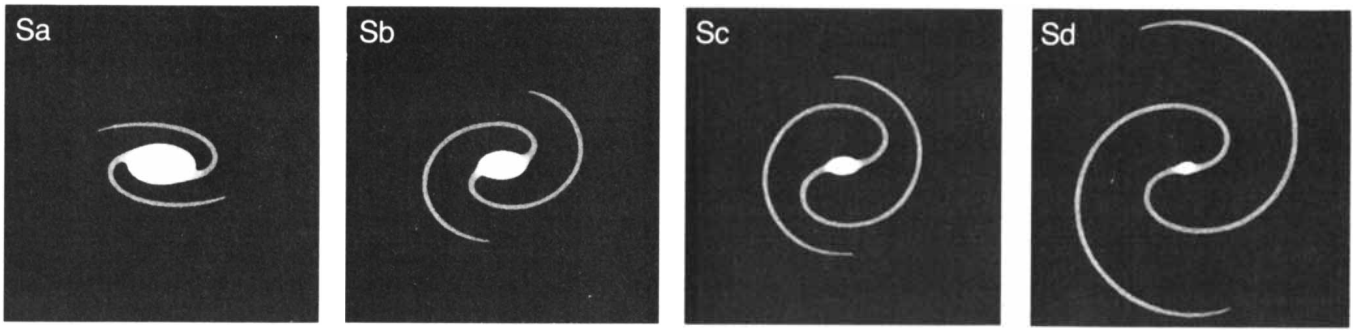
The relationship of the giant molecular clouds to the other components of the galaxy—the massive young stars, the more diffuse gas and the older stars—can provide an important key to understanding the vast galactic machine. Are giant molecular clouds assembled by the collision of numerous smaller molecular clouds or by the compression of diffuse atomic hydrogen? Is there always a molecular cloud near the young stars, and if there is, are the birthplaces of these stars deep within the cloud or near the surface? Stars might form near the surface if the collapse of the clouds is triggered by external factors such as the collision of one cloud with another.

The locations of massive young stars such as those in the Trapezium cluster can be pinpointed throughout the galaxy by the low-frequency radio emission generated in the ionized gas surrounding such stars. As might be expected, there is an excellent correlation between the H II regions and the clouds: virtually every known optical H II region or radio H II region equivalent in size to the Orion nebula has a molecular cloud near it. The largest and hottest clouds tend to be associated with these H II regions. Inasmuch as the spiral arms of galaxies beyond our own are best delineated by the H II regions, the correlation seems to suggest that most of the giant clouds are in the arms of our galaxy. As it happens, there are many more giant molecular clouds in our galaxy than there are known giant H II regions (5,000 as opposed to about 200), and many of the cooler, smaller clouds are clearly not near any H II regions. Therefore one must be cautious in interpreting carbon monoxide observations made at low sensitivity or poor angular resolution. Such data would tend to resemble spiral arms because of an observational bias toward the largest, hottest clouds, even if clouds of all sizes and temperatures were fairly uniformly distributed.

A recent model proposed by John Y. Kwan of Bell Laboratories and the University of Massachusetts at Amherst implies that the existence of particularly large clouds in the arms could be explained if smaller clouds from the zones between the arms collide and coalesce, forming a few superclouds, or cloud clusters, when they reach the arms. If the frequency of cloud collisions is high-



DISTRIBUTION OF MOLECULAR CLOUDS in M51, the Whirlpool galaxy (*left*), is strongly correlated with the distribution of far-infrared radiation from young stars in the same galaxy (*right*). The contours in both cases indicate increasing concentration toward the galactic center. The similarity between the two distributions suggests that the young stars are formed in the clouds and that the rate of star formation is directly proportional to the amount of molecular gas at each point. The molecular-cloud map is based on carbon monoxide data obtained by the authors with the 14-meter radio telescope in Massachusetts. The far-infrared map was made by James Smith and his colleagues with the aid of NASA's C-141 airborne observatory. Note the lack of any strong correlation with the galaxy's spiral arms.



SPIRAL GALAXIES range from type *Sa* galaxies, which have a tight arm structure and a large central bulge, to type *Sd* galaxies, which have an open arm structure and a fairly small central bulge. Our galaxy is believed to have an intermediate, type-*Sbc* structure.

er in the arms, this could account for the higher rate of massive-star formation there. When clouds collide, it is expected that the compression of the gas at the interface would be followed by the collapse of the cloud fragment into one or more protostars. Such compressed regions would be favorable to star formation because the self-gravity of the cloud fragment would be increased as a result of the higher density.

Once the massive stars are formed their high luminosities heat the surrounding dust cloud. Hence the correlation of hot clouds with the locations of the H II regions is quite understandable. After the superclouds leave the arms they may break up into smaller units, perhaps as a result of the disruptive forces of the hot H II regions.

The observation of widespread molecular gas in our galaxy raises basic questions that can be addressed only by looking at other galaxies. For example, is the ring of molecular clouds at a radius of approximately 15,000 light-years from the galactic center a common feature of other galaxies? Is it a mark of the way our galaxy was originally shaped or has our galaxy simply evolved to this form in the course of aging? Is the comparative abundance of molecular gas seen in the interior of our galaxy a general characteristic of most spiral galaxies? Do the quantity and the distribution of molecules in a galaxy depend on the form of the galaxy? Finally, how is the total luminosity of a given galaxy dependent on the quantity and the distribution of molecular clouds? One might expect some relation between the two if a large fraction of the galaxy's energy is generated by young stars that form within the clouds.

It is now well established from optical studies that the stellar properties of galaxies follow predictable patterns. In his pioneering work on galaxies Baade observed that the stars can be divided into two classes. One class, whose members were young, blue stars, he called Population I; the other, whose members include old, red stars, he called Population II.

In the elliptical and lenticular galaxies the stars are almost all older than five billion years. Except in a few instances there is little evidence of either the young, Population I stars or substantial interstellar gas to form future generations of stars; in such galaxies the supply of gas either was exhausted long ago or has been swept out into the surrounding intergalactic space. These galaxies contain primarily Population II stars.

In spiral galaxies such as ours both populations are present. The old, Population II stars occupy a spheroidal volume resembling an elliptical galaxy, whereas the young, Population I stars are found almost exclusively in the thin disk along with nearly all the remaining interstellar matter. Both the spheroidal distribution of old stars and the younger disk have a common center. Among spiral galaxies the relative blend of the old and the young components can vary greatly, ranging from the early-type spirals (designated *Sa*), which have a large nuclear bulge and tightly wound spiral arms, to the late-type spirals (*Sd*), which have an almost insignificant visible nucleus and a very open, patchy spiral pattern. Our galaxy is thought to be an *Sbc* type with intermediate characteristics. Within each morphological class there is a wide range of mass and luminosity, typically covering a factor of between 10 and 100 in total energy output.

Early studies of the radiation emitted by molecules in other galaxies were conducted by Lee J. Rickard of Howard University and Patrick Palmer of the University of Chicago. These astronomers concentrated initially on investigating the galaxies that have abnormally strong infrared emission. In these galaxies, it was believed, a burst of star formation was fueled by a plentiful supply of molecular gas. Recently we have undertaken a comprehensive program to map the carbon monoxide emission in more normal spiral galaxies with the goal of elucidating the relation of the content and distribution of molecular gas to the morphology and luminosity of the galaxy. Our observations were made with the 14-meter radio telescope operated by the Five College Radio Astronomy Observatory in Massachusetts; it is the largest such instrument in the U.S. and provides a high angular resolution, enabling us to observe fine details in the external galaxies. Of the 80 galaxies we have studied, almost 40 have shown detectable carbon monoxide emission, and 20 of them have been partially mapped. Most of these galaxies are classified as normal spirals, although a few are irregular.

Because of the great distances of the external galaxies, it is not possible to observe individual molecular clouds in them. The resolution of the 14-meter telescope (50 seconds of arc) does, however, enable us to look at the composite emission from regions typically 5,000 light-years across, encompassing many molecular clouds. The carbon monoxide observations of external galaxies therefore yield a determination of the global distribution of molecular clouds, not their individual properties.

One of the spiral galaxies studied most closely by several groups of radio astronomers is M51, the Whirlpool galaxy. Here the carbon monoxide emission is detected over the entire visible disk; as in many galaxies the greatest concentration of molecular gas is found near the center. Most surprising, however, is the fact that there is a fairly smooth, systematic decrease in concentration from the center out to where the emission becomes undetectable. In other words, there is no evidence of either a ring or armlike concentrations in the molecular gas. The absence of such concentrations may be attributable in part to insufficient resolution: the arms are quite narrow and have little space between them. The absence of a ring, however, is clearly significant: if there were a feature similar to the one in our galaxy, it would be easily observable.

An important clue to understanding how the rate of star formation varies across the disks of galaxies is derived from a comparison of the molecular distribution in M51 with the distribution of luminosity, particularly the luminosity of the youngest stars. With the aid of a telescope carried on the National Aero-

nautics and Space Administration's C-141 airborne observatory, James Smith of the Yerkes Observatory has recently made a complete map of M51 in the far-infrared part of the spectrum at wavelengths between 80 and 200 micrometers. This radiation is contributed partially by sources similar to the bright infrared sources behind the Orion nebula, which are presumably young star clusters formed in the past 10 million years and still shrouded in dust. The total luminosity measured by Smith in the far-infrared band is 30 billion solar luminosities within the region of the optical disk out to a galactic radius similar to that of the sun in our own galaxy.

Of fundamental importance is the finding that there is virtually a one-to-one proportionality between the far-infrared luminosity and the carbon monoxide emission at different points in M51. Both fall off smoothly with distance from the center of the galaxy, and the dependence on radius is nearly identical. If the rate of star formation is indicated by the energy output in the infrared band, and if the supply of gas capable of forming stars is indicated by the carbon monoxide emission, then one might conclude that the rate of star formation depends solely on the abundance of the molecular clouds, not on their location in the galaxy.

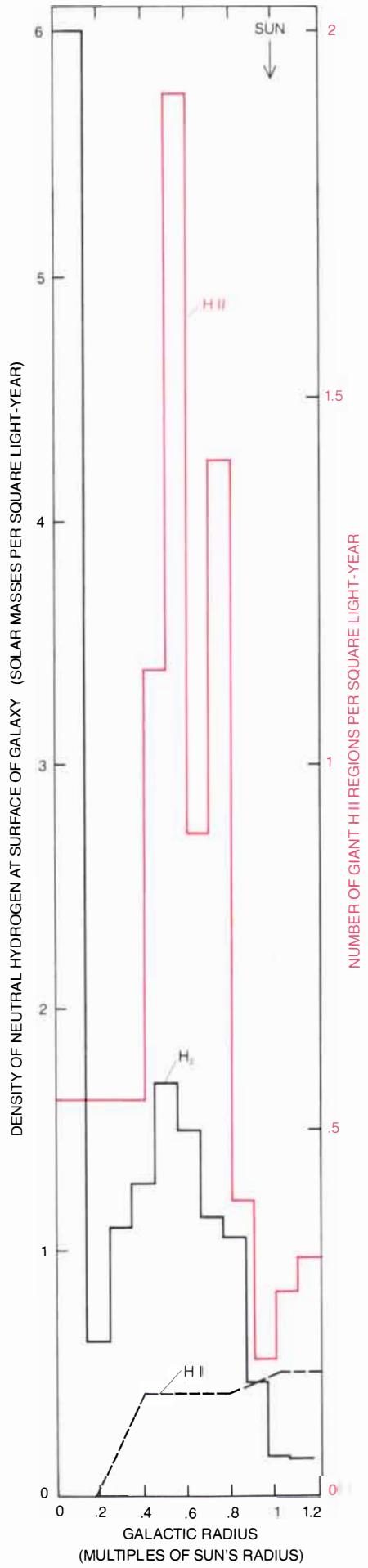
At first this conclusion seems surprising, because it is expected that the external forces promoting the collapse of the clouds to form stars might depend strongly on distance from the center of the galaxy. Perhaps a natural explanation of the simple correlation between the rate of star formation and the mass of molecular matter is to be found in the nature of the clouds. If the clouds in M51 are primarily giant clouds like those in our galaxy, it is difficult to see how external phenomena such as the expanding shells of supernovas and H II regions could penetrate very far inside the clouds. The inertia of a cloud with a mass a million times that of the sun is simply too great for a significant fraction of the cloud to be affected. In a sense the clouds are already pregnant with star formation, and an external stimulus that penetrates only the surface layers can do little to alter the total rate of stellar birth for the entire cloud.

The proportionality between the rate of star formation and the abundance of molecular gas found in M51 now appears to be a general rule in those late-type, high-luminosity spiral galaxies where the amount of molecular gas exceeds that of atomic gas. For most galaxies complete far-infrared data do not yet exist, but an approximate measure of the rate of star formation is obtained from the blue starlight in the galactic disk. This light is generated mainly by hot stars less than a few billion years old. For example, in the late-type spirals IC 342 and NGC 6946 (both classified as *Scd*) we have found similar variations with radius for the carbon monoxide emission and the blue light.

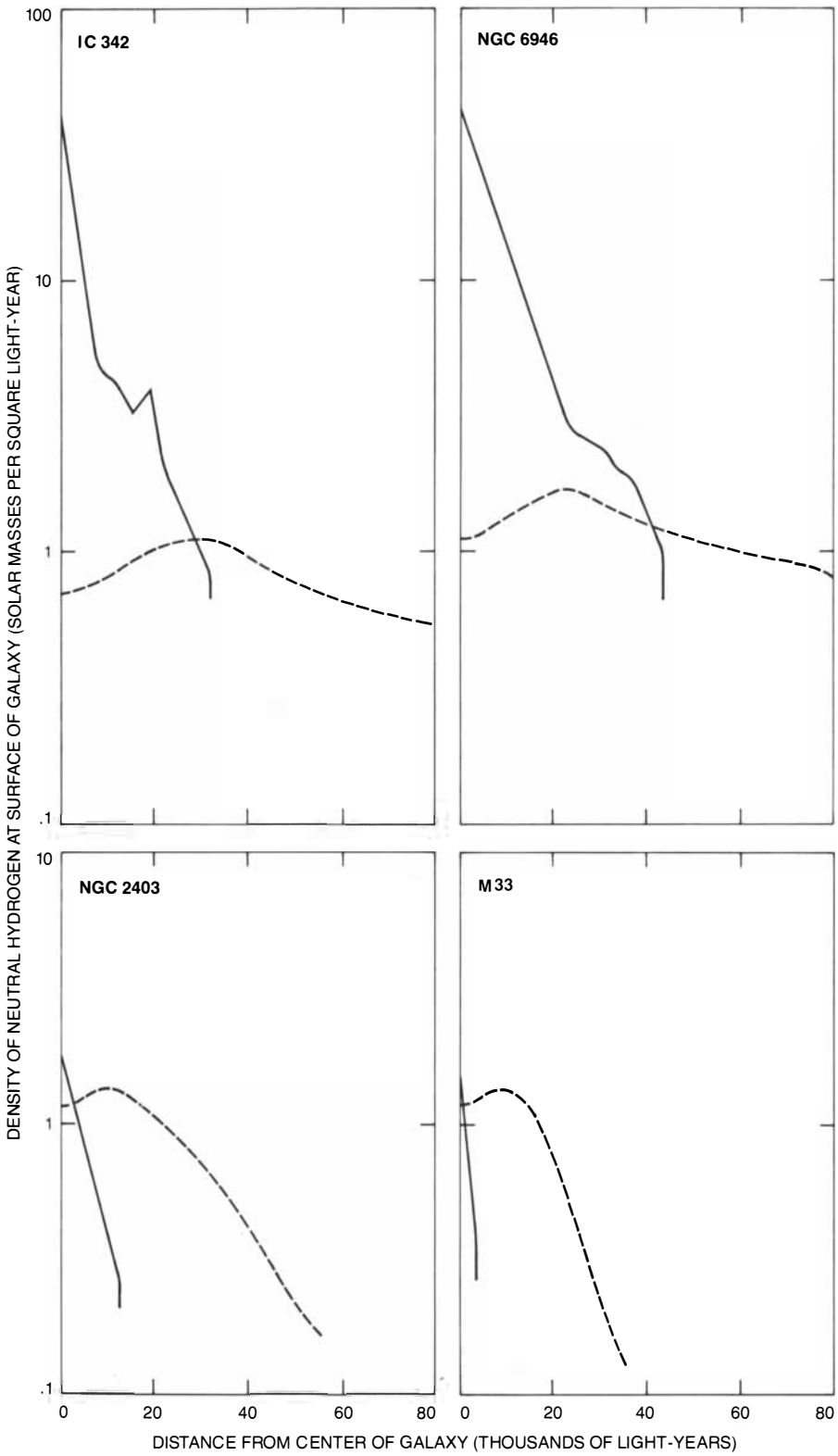
Since the carbon monoxide emission traces the distribution of the densest component of the interstellar medium, it is interesting to compare it with the emission from atomic hydrogen, which presumably traces the less dense (but still neutral) gas. Detailed studies of the atomic-hydrogen content and distribution in external galaxies have been made by many astronomers in the past 10 to 20 years. In spite of the wide range of luminosities of the *Scd* galaxies, all of them have similar distributions of atomic hydrogen, namely a fairly constant density throughout most of the disk except at the center, where there is a deficiency of H I.

In general the size of the atomic-hydrogen envelope for each galaxy is also much larger than the visible galaxy. The carbon monoxide content and distribution for the same galaxies are remarkably different, displaying little resemblance to the atomic-hydrogen profiles. Specifically, the galaxies with a high luminosity were found to be abundant in molecular clouds, whereas those with a low luminosity have only a small amount of molecular gas. The molecular distributions also exhibit steep gradients in the radial direction. Thus the high-luminosity galaxies have primarily molecular gas in the center and atomic gas in the outer regions, whereas the low-luminosity galaxies have mostly atomic gas throughout. In this respect our galaxy corresponds more closely to the high-luminosity external galaxies.

The expectation, of course, is that by looking at other galaxies we can come to understand features of our own galaxy. In view of the fact that our galaxy is intermediate along the sequence of spiral types, it was initially most surprising that none of the galaxies first observed for carbon monoxide showed a central peak and ring of molecular clouds like those in our galaxy. It is now apparent that this finding was at least partially attributable to observational selection: most of the galaxies first observed for



EVIDENCE OF A RING of star-forming material in our galaxy is presented in this chart. The line in color shows the distribution of giant ionized-hydrogen (H II) regions, a reliable indicator of where massive stars are forming the galaxy. The black line traces the distribution of molecular hydrogen (H_2). Both distributions exhibit a strong peak at approximately half the distance of the sun from the center of the galaxy. In contrast, the distribution of neutral (un-ionized) atomic hydrogen (H I), indicated by the broken black line, remains fairly constant, rising somewhat beyond the sun's orbit, where there are few giant H II regions.



COMPOSITION OF INTERSTELLAR MATTER in four galaxies of a similar type is closely related to the brightness of the galaxy. All four of the galaxies represented here are classified as type *Scd:* open spirals with a comparatively small nucleus. Near the centers of the two high-luminosity galaxies, IC 342 (*top left*) and NGC 6946 (*top right*), the ratio of molecular hydrogen, or H_2 (*black curve*), to neutral atomic hydrogen, or H I (*broken black curve*), is roughly 100 to one, whereas in the low-luminosity galaxies, NGC 2403 (*bottom left*) and M33 (*bottom right*), the amounts of molecular and atomic hydrogen are about the same. All four galaxies have similar peak values of neutral hydrogen at their surface, so that it is the amount of molecular gas that varies from galaxy to galaxy. In other words, the high-luminosity galaxies have much more molecular gas than the low-luminosity ones. The low-luminosity galaxies are also smaller, as is indicated by the limited extent of their atomic-hydrogen component. The observations of molecular hydrogen were made by the authors; the observations of atomic hydrogen were made by David H. Rogstad and G. Seth Shostak of the California Institute of Technology.

carbon monoxide were dusty *Sc* spirals, not intermediate types such as our galaxy. As more *Sa* and *Sb* galaxies are observed the ring is seen more often. The origin of the structure might be related to the size of the central, nuclear bulge of old stars.

In fact, if one compares the molecular distributions observed in all the spiral galaxies, their outer disks exhibit a rather similar, smooth decrease in concentration; the dissimilarities appear in the inner disks. In some of the galaxies there is a drop in the density of molecular hydrogen at the center; in others the density of the gas simply continues its increase from the outer disk all the way to the nucleus. This observation suggests that the significant feature is not the peak of the ring but the void that sometimes appears in the inner zone. A possible link between the size of the central-bulge star population and the existence of a breach in the gas distribution might materialize if the gas originally in this zone were exhausted at an early epoch to form the stars in the massive central bulge. Why some galaxies form a more massive bulge than others is a mystery of the initial constitution of galaxies.

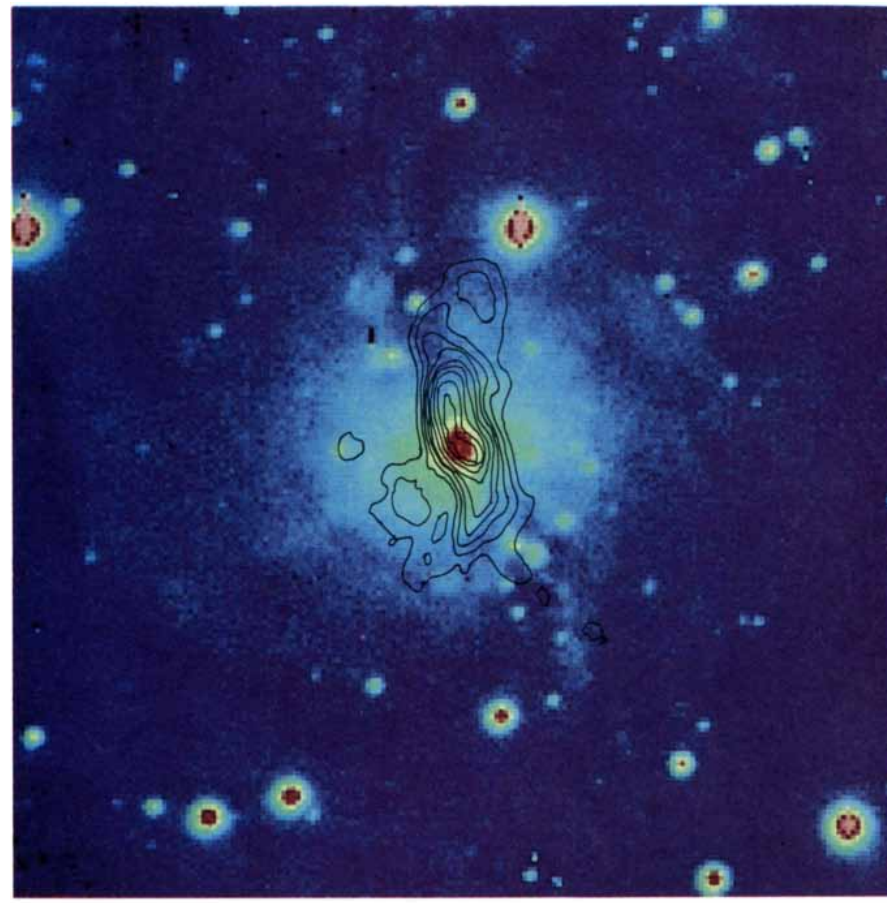
The general correlation of the carbon monoxide distribution and the optical luminosity, discovered by us originally in a few selected late-type spiral galaxies, also holds when one compares a sample of galaxies over a wide range of luminosities, all in a given morphological class. The results for the central regions of the type-*Sc* galaxies are quite striking: the optical luminosity varies in direct proportion to the amount of molecular gas. In other words, if more molecular clouds are present, more stars will form and a galaxy will have a correspondingly higher luminosity. This correlation is precisely the same as the one observed in individual *Sc* galaxies such as M51, where the distribution of carbon monoxide emission was found to mimic that of the young stars. The fact that the correlation exists both within particular *Sc* galaxies and between galaxies, however, indicates it is a general feature of star formation in galaxies of this type. If one were to compare the central atomic-hydrogen contents with the optical luminosities within the same sample of galaxies, one would find no correlation at all.

Perhaps the most enigmatic galaxies are the 10 percent or so whose central regions show energetic activity in the form of X-ray and radio emission, highly noncircular gas motions and powerful optical and infrared emission. At a very low level of activity the center of our own galaxy shows most of these symptoms. For the more extreme cases, such as the quasars, it is believed the activity is generated by an extraordinary object such as a massive black hole at

the center of the galaxy. For other cases it has been suggested that the activity is attributable to a burst of star formation. In the latter instance the massive young stars (up to a billion solar masses in the most extreme examples) will have an enormous luminosity for a brief period of about 10 million years; hence a burst of star formation could account for a high instantaneous energy output. Moreover, the supernova explosions coming at the end of the burst would generate high-velocity gas motions in addition to intense X-ray and radio emission. Clearly the duration of the burst is limited by the reservoir of interstellar matter near the center of the galaxy, since most of the gas will eventually coalesce into stars and the subsequent rate of star formation will decrease.

One of the nearest examples of these phenomena is the irregular galaxy M82. For many years it was believed the nucleus of this galaxy had exploded, because plumes of high-velocity ionized gas could be detected above and below the galactic disk. The filaments point radially away from the center of the galaxy just as though they were an outflowing gas stream. The prevailing view now is that many of the peculiarities observed outside the nucleus of M82 can be attributed not to gas flowing out of the galaxy but to intergalactic gas falling into it. The bridge of hydrogen extending across the sky to the nearby spiral galaxy M81 suggests that the infalling gas may have been pulled out of the outer halo of M81 in the course of a close encounter.

M82 is one of the brightest infrared sources beyond our galaxy. At its center the infrared luminosity is about 20 billion times the luminosity of the sun. Because of the great quantities of absorbing dust seen in the plane of the galaxy, the optical luminosity in the same region is a factor of 20 less. Not surprisingly, M82 has been found to be one of the brightest sources of carbon monoxide emission beyond our galaxy. It was in fact the first galaxy detected by Rickard and his colleagues on the basis of its carbon monoxide emission. An analysis of the motions of the molecular gas based on the Doppler effect on the emission reveals a structured pattern, with the receding gas to the north and the approaching gas to the south. Contrary to the situation in normal spiral galaxies, where the axis of rotation is perpendicular to the galactic disk, here one finds an axis tilted at nearly 45 degrees to the disk. This finding suggests the presence of large motions directed radially toward or away from the center of M82; in other words, the gas clouds have velocities significantly different from those of normal circular orbits. These peculiar motions are perhaps the consequence of an infall of gas from outside the galaxy.

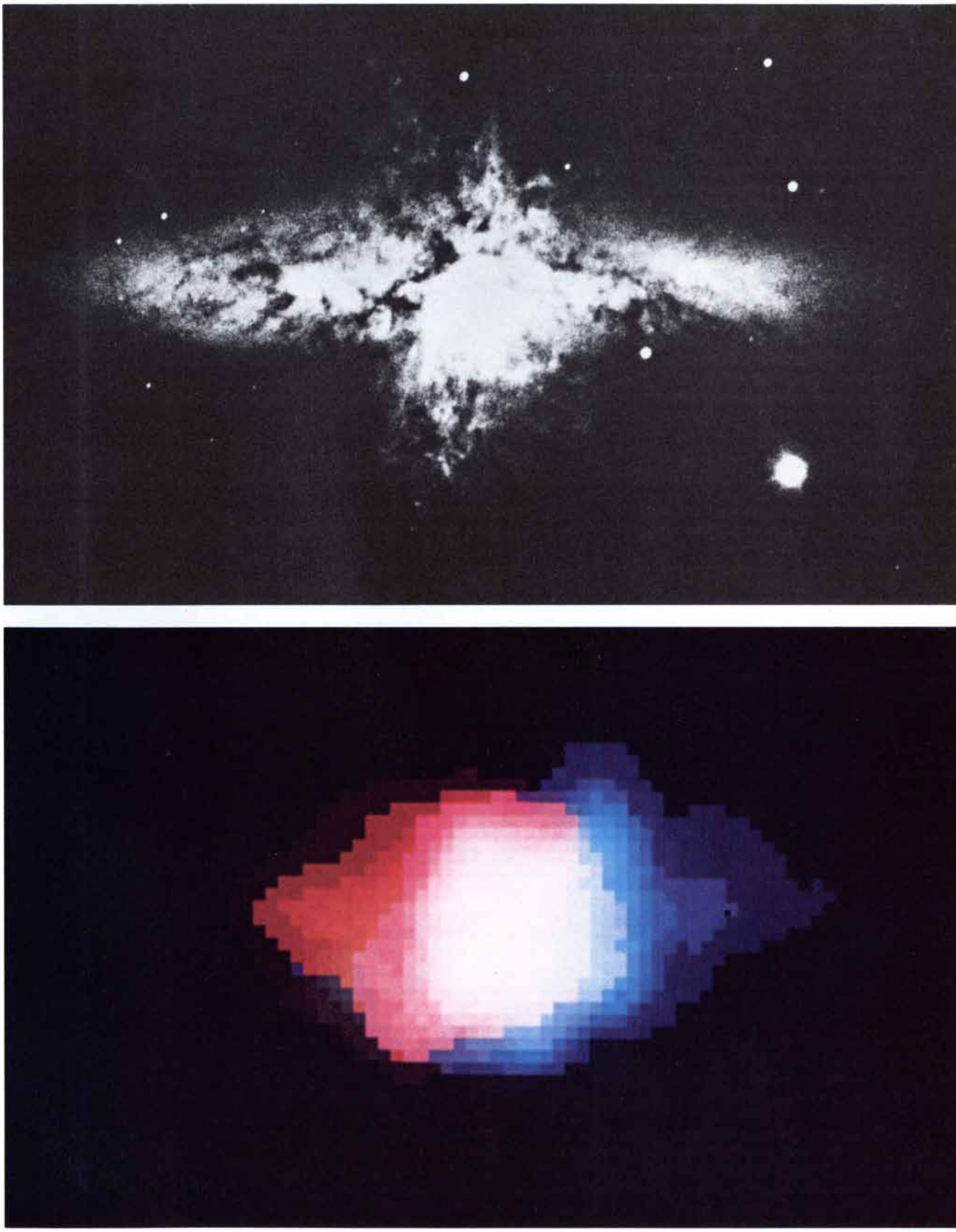


MOLECULAR CLOUDS IN THE NUCLEUS of the spiral galaxy IC 342 are confined to a bar-shaped region measuring about 6,000 light-years in length (*black contours*). The data suggest that the clouds are flowing in toward the center of the galaxy along the bar, possibly accounting for the high rate of star formation there. The molecular clouds were plotted on the basis of their 2.6-millimeter radio-wave emission from carbon monoxide molecules by Kwok-Yung Lo and his colleagues at Cal Tech, working with the new high-resolution, millimeter-wave interferometer at the Owens Valley Radio Observatory. The false-color optical image was obtained with a charge-coupled device attached to the 60-inch telescope on Mount Wilson.

Further study of the carbon monoxide emission from M82 shows that the greatest concentration of molecules is at the center of the galaxy near the peak in the far-infrared emission. The density of the molecular gas exceeds that of atomic hydrogen over the entire optical disk and well up into the vertical filaments. Indeed, the total mass of molecular gas in the galaxy is almost half the total mass of the stars, or roughly three times the fraction observed in normal spiral galaxies. In many respects the peculiarities observed in M82 bear a strong resemblance to what one would expect of a young galaxy: a stellar population with a high proportion of massive, short-lived stars, an abundance of interstellar gas not yet coalesced into stars and continuing infall of intergalactic gas from the outer part of the protogalactic cloud. Could we be witnessing here the birth—or, more likely, the rejuvenation—of an entire galaxy?

In some galaxies, particularly those with a fairly modest rate of star formation in the central region, the activity in that region might be initiated and sustained by the infall of gas from the outer disk of the galaxy. A good example of the phenomenon is presented by the galaxy IC 342. Kwok-Yung Lo and his colleagues at Cal Tech have recently mapped the carbon monoxide emission in the nucleus of this galaxy with the new high-resolution, millimeter-wave interferometer at the Owens Valley Radio Observatory. Their data clearly show for the first time that the molecular clouds in IC 342 are confined to a barlike structure about 6,000 light-years long. The measured velocities of the clouds suggest a significant infall toward the center of the galaxy where previous infrared observations had indicated a higher-than-normal rate of star formation. The bar may act to channel gas clouds into the central zone.

At an even higher level of activity is the spiral galaxy NGC 1068. It is in a class of galaxies distinguished by their extraordinarily bright and compact optical nuclei, which exhibit strong emission lines from high-velocity ionized gas. The far-infrared luminosity is a staggering 200 billion solar luminosi-



VERY PECULIAR GALAXY, M82, is observed at two different wavelengths. The black-and-white photograph at the top was made in red light with the 200-inch telescope on Palomar Mountain. It shows a generally amorphous disk with dark dust lanes silhouetted against its surface and a tangled array of filaments extending outward at right angles from the center of the disk. The color image at the bottom, based on the 2.6-millimeter emission from carbon monoxide molecules in the same region, was made by the authors. The brightness of the image is proportional to the intensity of the emission. The colors represent the velocity of the gas with respect to the center of the galaxy; red corresponds to gas that is moving away from the viewer and blue to gas that is approaching. The data indicate that the gas in the disk is rotating in a plane along the line of sight and that the gas in the filaments is falling in toward the galactic center.

ties, all originating from the central 5,000 light-years. This galaxy is also extremely rich in molecular gas, as can be judged from the strong carbon monoxide emission. Nevertheless, it is clear that the current level of activity can be sustained for no longer than a few hundred million years if the luminosity is produced by young stars and the supply of star-forming material is limited to what is now seen in the central regions. It is difficult to understand how the supply in the central region can be replenished by transport from the outer disk, where the gas is currently in a circular orbit. Thus bursts of star formation have usually been favored to explain these galaxies, and activity in the central region is probably sporadic.

One of the most intriguing questions for the star-burst models is what regulates the process. How does the burst start, why does it spread and how is the fire quenched? It may be that the activity in the molecular clouds distributed throughout the inner galactic disk is triggered by activity in the central object: a black hole, if one exists. NGC 1068 appears to show both kinds of activity. A source less than 100 light-years in diameter has an infrared, optical and X-ray luminosity of nearly 100 billion suns. Presumably this energy originates in a central compact object. At the same time there is clear evidence that the far-infrared luminosity of a similar magnitude originates in a disk of clouds extending over at least a few thousand light-years. Perhaps the central source stimulates star formation in the outlying clouds by sending explosive shock waves through the galaxy. Alternatively it could be that the region is inert until a critical mass of star-forming material accumulates; then a small initial spurt of star formation might not only become self-sustaining but also lead to a runaway chain reaction of massive-star formation. At present the molecular observations cover too few galaxies for one to tell if there are some galaxies with a large abundance of gas but little active star formation, as would be suggested by the second possibility. In addition the second possibility leaves unanswered the question of the nature of the central object.

It is now well established that most stars must form in molecular clouds. This conclusion follows from studies of nearby star-forming regions such as the Orion nebula; it also is implied by the strong correlation found in the external galaxies between the molecular gas and the radiation from young stars. The other major gaseous component of these galaxies, atomic hydrogen, does not show this correlation.

In spite of the understanding gained in the past few years, astronomers are still left with perplexing questions about the nature of the spiral arms in galaxies. What is this phenomenon that dominates the visible morphology of galaxies? Is an arm merely a phase change in the galactic disk, like the puffy white clouds in the earth's atmosphere, or is an arm more substantial in structure, perhaps a wave in the density of matter that propagates through the galactic disk? The answer has been elusive partly because the nature of the arms in one galaxy, or even in one region of a galaxy, may differ from that in another.

The observational studies of molecular gas have clearly demonstrated that the abundance of molecular clouds can vary greatly among galaxies and at different radii within the same galaxy. If the existence of molecular clouds is a prerequisite for star formation, then in galaxies with large amounts of molecular gas that condition will be satisfied throughout the disk. In such cases one expects the patterns of star formation to be much less ordered and coherent, since star formation will be widespread. On the other hand, for those galaxies where the amount of molecular gas is low, the condition may be satisfied only in certain places. In these latter galaxies it then becomes much easier for a grand spiral pattern of star formation to arise with molecular clouds only along the arms. Clearly in analyzing the large-scale patterns of star formation one must consider separately those galaxies with an abundance of molecular gas, such as our galaxy, and those with a small amount, such as M31 (the Andromeda galaxy) or M81. Those two galaxies are often cited as examples of the kind of grand spiral pattern consistent with the density-wave theory; they are also both extremely deficient in molecular gas. The low abundance of molecular gas is consistent with the finding by Richard A. Linke and Anthony Stark of Bell Laboratories that the carbon monoxide emission in M31 is closely confined to the visible spiral arms.

The major problem in understanding spiral structure is not how a curved arm is formed but rather how the structure is maintained over a long time and becomes symmetrical about the center of the galaxy. It is well known that any disturbance moving radially in the disk of a spiral galaxy will be forced into a spiral simply as a result of the galaxy's rotation. Typically it is found that the speed of rotation in a galaxy is fairly constant with radius over most of the disk, implying that matter orbiting at a large radius will lag and matter orbiting at a small radius will advance (with respect to a rotating point of origin midway between them). Thus in these galaxies any effect such as an explosion or a rash of star formation spreading from one cloud to another would naturally form a curved arm. The difficulty arises when one tries to coordinate the phenomenon over the entire disk.

It now seems possible that much of the confusion on this subject may be the result of attempting to force the coherence and symmetry of a spiral pattern on all galaxies rather than simply accepting the fact that there are some galaxies, perhaps a majority of them, where there is little evidence of coherence. In this picture the galaxies with a truly coherent spiral pattern would be those such as M31 and M81, which have a comparatively low abundance of star-forming clouds, or those such as M51, which has a companion galaxy sufficiently close to exert a major tidal pull over the entire galactic disk. In the remaining galaxies with an abundance of clouds the formation of stars will be more widespread and less organized.

One indisputable fact is that the arms, such as they are, are places where massive stars form. Whether there is an enhancement in the rate of formation of all stars in the arms or just a shift in the relative proportion of massive stars is not known. Within the next decade one can look forward to the answer to this important question, since satellite-borne infrared telescopes aimed at the external galaxies will have enough angular resolution to clearly separate their arms and the regions between the arms.

Through observations of the large-scale distribution of molecular clouds, both in our galaxy and in other galaxies, understanding of the relations between these cold, dense regions and the global properties of galaxies such as morphology and luminosity has been deepened. Since the molecular clouds are the precursors of star formation, it is now possible to obtain a wealth of information on a crucial phase in the life cycle of stars and to begin to understand the evolution of galaxies.

It has been supposed that most of the organic matter in the universe (that is, carbon compounds more complex than carbon monoxide) must be on the surface and in the atmosphere of planetary bodies. The enormous mass of the molecular clouds implies, however, that they are the principal reservoirs of organic matter. Moreover, if the solar system were to pass through one of these clouds, the absorption of light would be so great that all but the few nearest stars would disappear from view. If the sun traveled with a typical stellar velocity of 20,000 miles per hour, more than two million years would elapse before the earth emerged from the gloom. Given the abundance of the clouds in our galaxy, such an event must come roughly once every billion years, or about five times in the history of the earth. If human beings had evolved during such an episode, both their vision of the universe and their philosophical outlook would have been fundamentally different.

The Diamond-Anvil High-Pressure Cell

This ingenious device makes it possible to replicate the pressure near the core of the earth by turning a thumbscrew. Its widespread application has revolutionized the study of high-pressure phases

by A. Jayaraman

In the vestibule of my laboratory at AT&T Bell Laboratories is a large hydraulic apparatus, standing seven feet high, weighing several tons and held in place by four stout pillars of steel. A solid substance placed in the jaws of the device can be squeezed to a pressure of up to 100,000 times that of the earth's atmosphere at sea level, or more than 100 times the pressure at the bottom of the deepest part of the oceans. At such pressures the forces imposed on solid matter are so great that the lattice of atoms forming the solid can deform and the electrons wandering through the solid can take on unusual states of energy. These microscopic changes can profoundly alter the macroscopic properties of a substance: its density, color, opacity, ductility, electrical conductivity and susceptibility to a magnetic field. Moreover, the exploration of such changes in the laboratory is by no means a pure exercise in physics. Much of the matter in the universe, including most of the matter that makes up the earth, is confined at pressures far greater than 100,000 atmospheres. It would appear that a press much larger than the one in my vestibule is needed to reach the pressures common in the deepest regions of the planet.

Allow me to show you the rest of my laboratory. Although my work is concerned almost entirely with the properties of matter under enormous pressure, most of the laboratory space is now given over to instruments that play ancillary roles in the investigation: the laser, the microscope, the spectroscope and the automatic equipment that can record the spectroscopic data. Indeed, it would be easy to miss the novel device that makes the rest of the work possible, because it can be held readily in the palm of one hand. In spite of its size, the device can routinely create pressures 10 to 15 times as great as the highest pressure that can be reached with the hydraulic press. The greatest pressure recorded so far with the device is 1.7 million atmospheres, which is the equivalent of the pressure 2,900 kilometers below the surface of the earth.

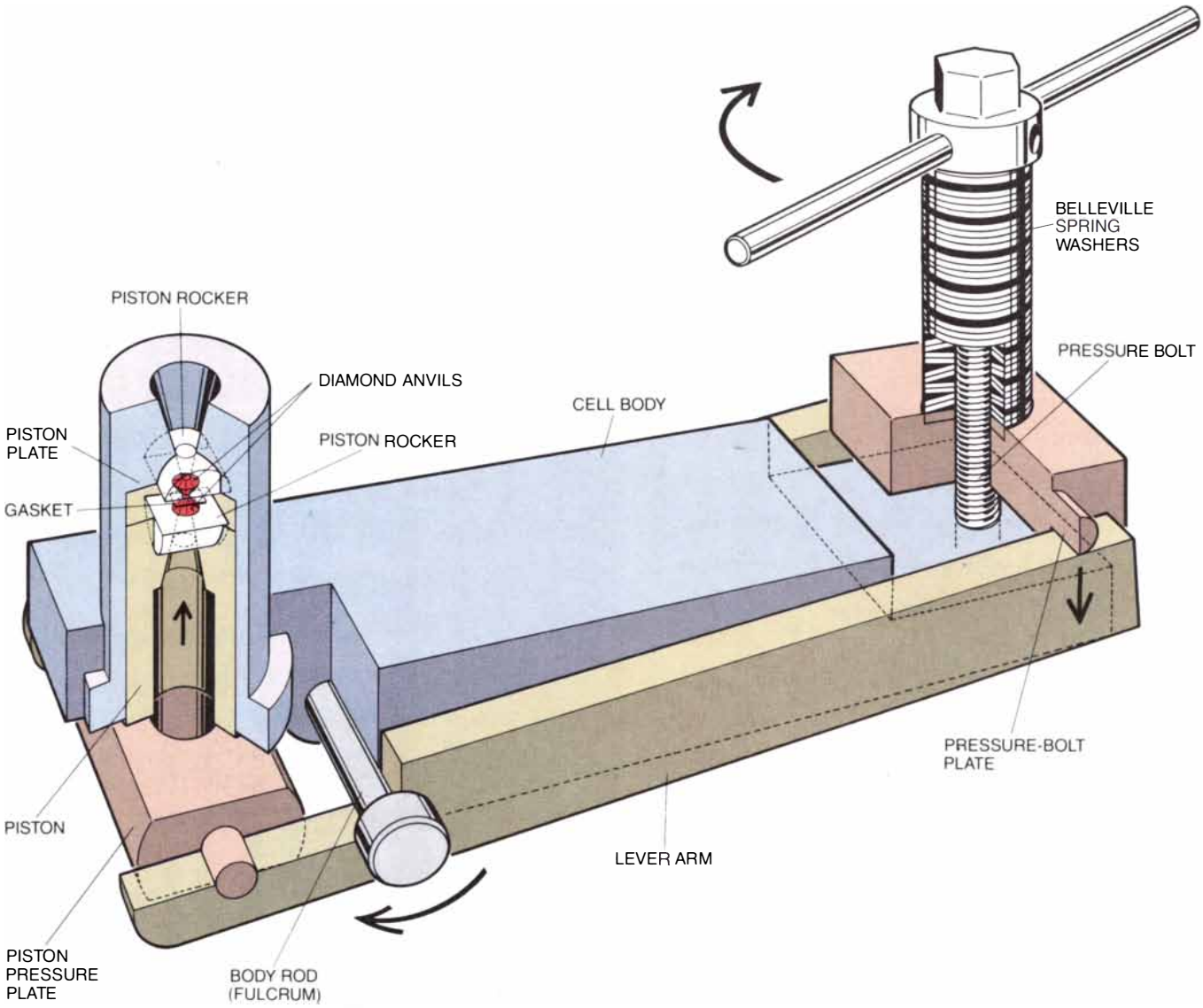
At the center of the new device are two flawless, gem-cut diamonds, each from a third of a carat to a half carat in weight. The points of the diamonds are ground off to small, flat surfaces set in opposition to each other. The two diamonds are mounted inside a hardened-steel mechanism, machined to high tolerances, that imparts thrust along an axis perpendicular to the diamond faces. There are at least five practical designs for the thrust mechanism, but in principle each one is little more than an elaborate nutcracker. A minute sample of the material to be studied under high pressure is placed between the faces of the diamonds, and a force that can be applied by hand is multiplied 500 to 1,000 times by the mechanism and transmitted to the sample between the diamonds. Because the area over which the force is concentrated is extremely small, the pressure on the sample, which is the force per unit area, can be enormous. Any such device, in which two opposing diamond faces apply pressure to a sample, is called a diamond-anvil cell.

The simple operation of the diamond-anvil cell is the hard-won result of 20 years of evolution in design. It is relatively easy to generate high dynamic pressures for a few millionths of a second with a shock wave, but the generation of high static pressures is as challenging as the study of the properties of materials subjected to these pressures. A basic problem is the containment of the sample of material under investigation: the walls of the container are subject to the same pressures as the sample is, and so the potential for deformation or fracture of the container must be taken into account. Furthermore, because the pressure on the sample must be hydrostatic, or equal in all directions, the sample inside the high-pressure cell must be surrounded by a soft or fluid material. If the sample and the hydrostatic material are to be loaded conveniently into a reusable cell, there must be a gasket system that can seal the loaded cell against leakage. Finally, the properties of the sample must be determined while the cell is under pressure; if the effects of variables such as temperature are to be studied at high pressures, these too must be controlled and measured without reducing the pressure inside the cell.

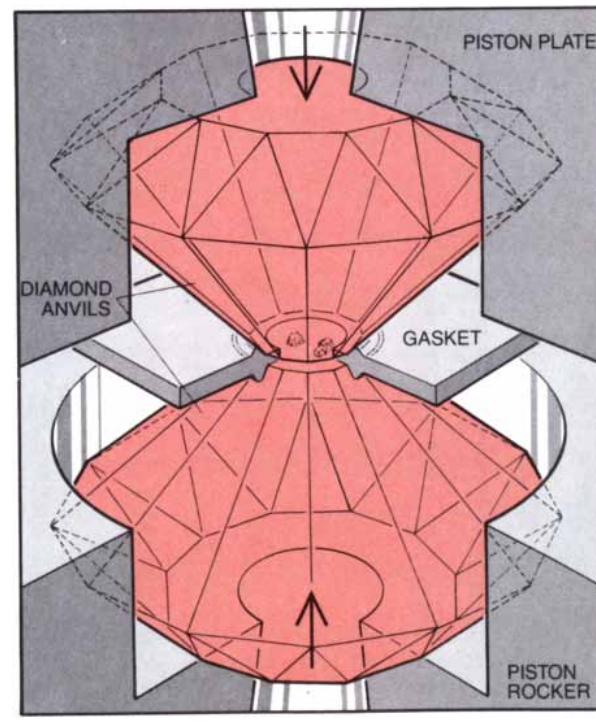
P. W. Bridgman of Harvard University pioneered the study of matter under high pressures almost single-handedly for more than half a century until his death in 1961. Not only did Bridgman study a remarkable number of elements and compounds under high pressure but also he invented every technique he worked with. He introduced a gasketing system for confining a sample between two anvils opposing each other along a single axis, and he used anvils of tungsten carbide, an extremely hard material of high compressive strength. To maintain hydrostatic pressure he surrounded the sample inside the high-pressure chamber with silver chloride, a soft, solid material that can transmit pressure evenly over the surface of the sample.

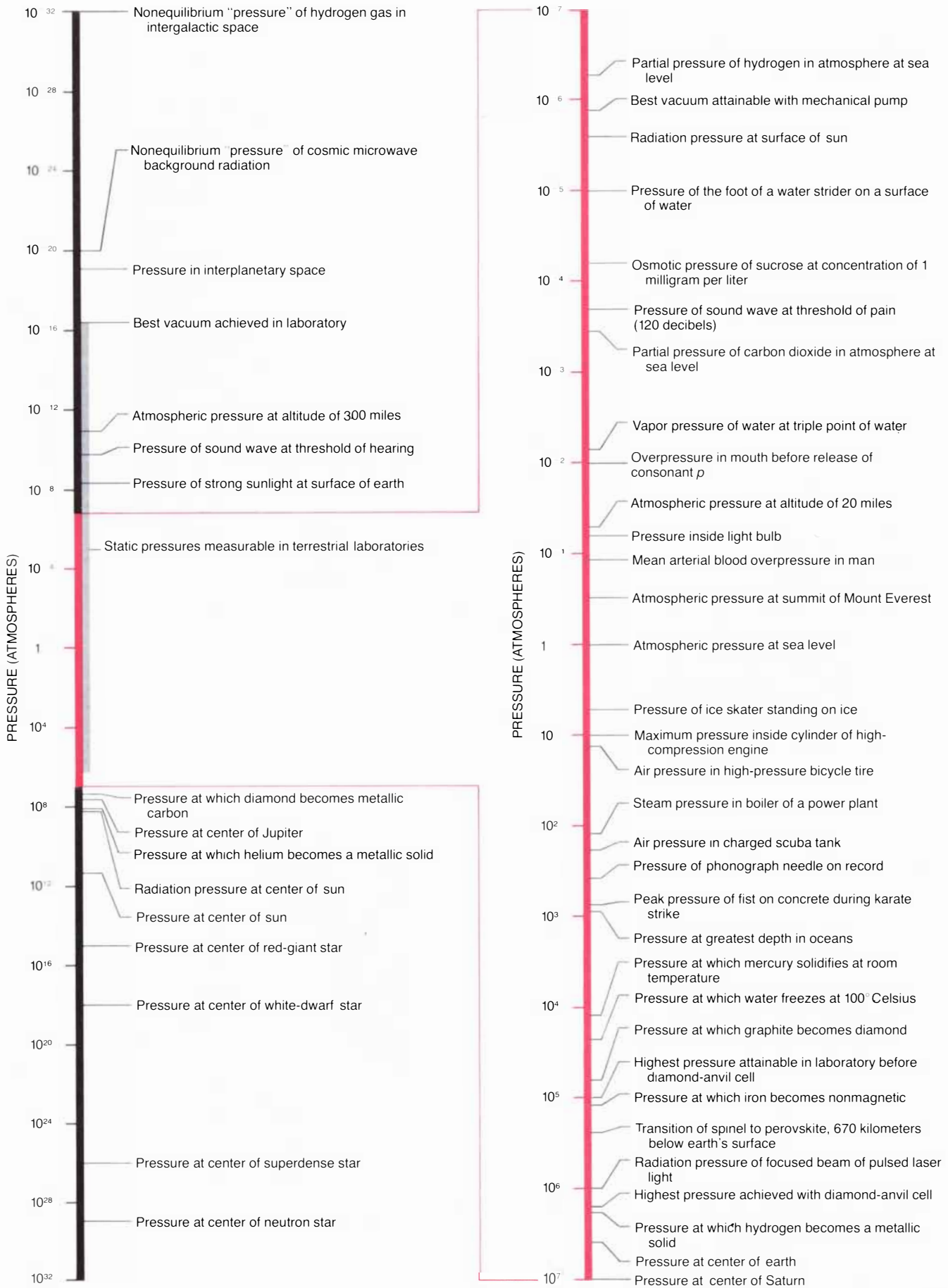
In 1905, while he was still a graduate student, Bridgman discovered to his surprise that the high-pressure chamber between two anvils could be sealed with a packing of soft material. The pressure on the packing material was always greater than the pressure inside the chamber, and so the packing served as a gasket that would not leak no matter how high the pressure was. Such basic refinements in technique enabled Bridgman to investigate the properties of matter at pressures as high as 100,000 atmospheres.

Bridgman anvils are limited by the compressive strength of tungsten carbide and by the opacity of the material to all radiation. It may therefore seem



THRUST MECHANISM of the diamond-anvil cell developed at the National Bureau of Standards is a simple, hand-held device made to close tolerances out of hardened steel. The machine shown above is a slightly modified version of an apparatus developed at the Geophysical Laboratory of the Carnegie Institution of Washington; it is about 20 centimeters long and weighs about three kilograms. In principle its operation is similar to that of a nutcracker. Thrust is generated by turning the handle on the pressure bolt clockwise. The thrust is then transmitted by the lever arm to a movable piston, which is recessed at the top to support the rounded surface of a half-cylindrical rocker mount. A diamond is fixed in place on the flat surface of the half cylinder, and the point of the diamond is ground flat. The flat face of this diamond, which is the lower diamond shown in the enlargement at the right, is thrust against the flat face of the upper diamond in order to generate pressure in the high-pressure cell. The upper diamond is also mounted on a half-cylindrical rocker, set at a right angle to the lower half cylinder; parallel alignment of the two diamond faces is then secured by tilting the two half cylinders until the fringes of optical interference set up by the two faces are reduced to a uniformly gray pattern. The cell is simply a small hole drilled in a sheet of steel and mounted between the two faces. A sample of the material to be studied at high pressure, a ruby for pressure calibration and a drop of fluid for transmitting the pressure evenly in all directions are placed in the cell. As pressure is applied the steel extrudes around the diamond faces, and so it serves as a gasket for the containment of the material in the cell. The stack of Belleville spring washers acts as a spring for loading the pressure bolt. Each spring washer is shaped like an ordinary washer with a bulge along its perpendicular axis, and the spring washers can be stacked so that the bulges face either in the same direction or in opposite directions along the bolt. By rearranging the spring washers the stiffness of the spring can be changed, and so the amount of thrust for a turn of the bolt can be varied. The device shown has generated a pressure of 1.7 million atmospheres.





RANGE OF PRESSURE in the universe is plotted over more than 60 orders of magnitude on two logarithmic scales. The scale at the right is an expanded version of the central part of the scale at the left. The diamond-anvil cell has extended the previous limit of static high pressures accessible to study by more than an order of magnitude. Transitions shown at higher pressures are predicted by theory.

surprising that diamond was not employed from the first as an anvil material. It was known in Bridgman's time, of course, that diamond is transparent to light and is harder than tungsten carbide. It is also transparent to X rays and is still the hardest substance known to science. Nevertheless, it was not until 1959 that diamond was fashioned into an anvil device for high-pressure investigation by Charles E. Weir, Ellis R. Lippincott, Alvin Van Valkenburg, Jr., and Elmer N. Bunting of the National Bureau of Standards and independently by John C. Jamieson, Andrew W. Lawson and Norman D. Nachtrieb of the University of Chicago. Since that time workers at the Bureau of Standards and elsewhere have developed the original device into a fine tool for quantitative high-pressure investigation.

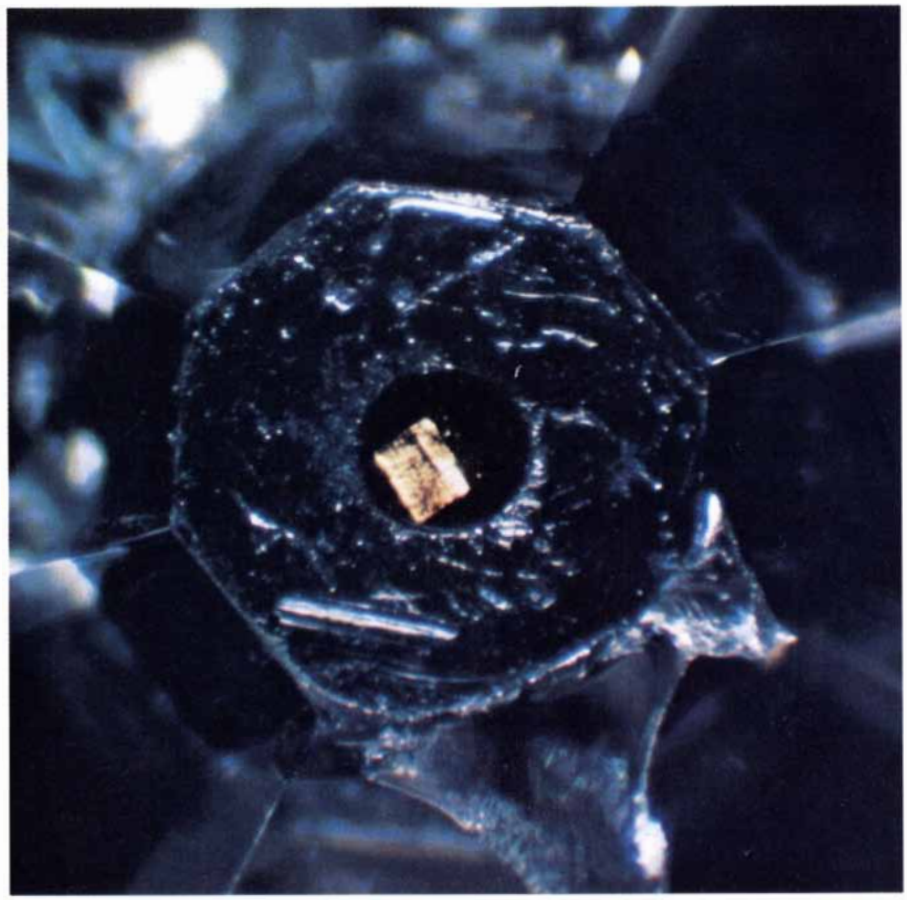
How is a sample loaded into the diamond-anvil cell and squeezed to a predetermined pressure? In my laboratory I am fortunate to have the assistance of Ralph G. Maines, a watchmaker by training, who has a deft hand with high-precision tools that must be manipulated under the microscope. The first step is to prepare the high-pressure cell, which is simply a hole drilled in a piece of sheet metal. When the sheet metal is mounted between the faces of the two diamonds and the hole is aligned with the thrust axis, the matter in the hole can be subjected to a high pressure. The metal surrounding the hole is extruded away from the diamond faces as pressure is applied, and so the metal serves as a gasket that seals the space around the sample [*see illustration on page 55*].

In order to center the hole on the thrust axis the stock metal is indented by the diamonds, and the hole, only 200 micrometers in diameter, is drilled as close as possible to the center of the indentation. The high-pressure cell that results is a cylinder 200 micrometers across and as deep as the thickness of the pressed sheet metal: about 100 micrometers. The gasket is seated on the face of the lower diamond in the same orientation as it had when the indentation was made. The sample material and a small ruby chip for the calibration of pressure are then placed in the hole. Finally, in order to maintain hydrostatic pressure the hole is filled with a drop of fluid from a syringe and then quickly sealed by the diamond faces before the fluid evaporates.

The ruby placed in the cell with the sample makes it possible to determine the pressure in the cell to a high degree of accuracy. Indeed, without the ruby the small size of the high-pressure cell would make the pressure quite difficult to calibrate, and the scientific value of the instrument would be far less than it is. When a ruby is excited by light, it fluoresces a strong, deep red. The fluorescent emission can be resolved by a spectrograph into two peaks whose wavelengths are accurately known at atmospheric pressure. When the pressure on the ruby is increased, the fluorescence peaks both shift to a higher wavelength. The shift has been calibrated for pressures known on independent grounds, and so the measured shift of the peaks in the ruby spectrum is an indirect measure of the pressure on the ruby. The spectral shift of the peaks is almost exactly proportional to the pressure for pressures of up to 300,000 atmospheres; for higher pressures the spectral shift is somewhat smaller for a given increment in pressure, but the pressure can still be estimated from the fluorescence.

There are several materials currently employed as hydrostatic mediums in the cell. The most convenient material to load into the cell is a mixture of four parts methanol to one part ethanol, but at pressures of more than 104,000 atmospheres the mixture freezes at room temperatures and its action is no longer strictly hydrostatic. Hydrostatic pressures can be maintained up to about 300,000 atmospheres by submerging the cell in liquid nitrogen and then trapping in the cell a noble gas such as xenon. Xenon freezes at about 112 degrees below zero Celsius, but it is an excellent hydrostatic-pressure medium in its solid form and does not react chemically with the sample. At higher pressures solid helium and solid hydrogen appear to be hydrostatic up to at least 700,000 atmospheres, but they require either that the cell be refrigerated to a temperature only a few degrees above absolute zero or that there be a means of delivering the hydrogen or the helium to the cell at high pressure.

After the cell has been loaded and pressurized the diamond acts as a window on the sample, and changes in the color or the luster of the sample with pressure can be directly observed in



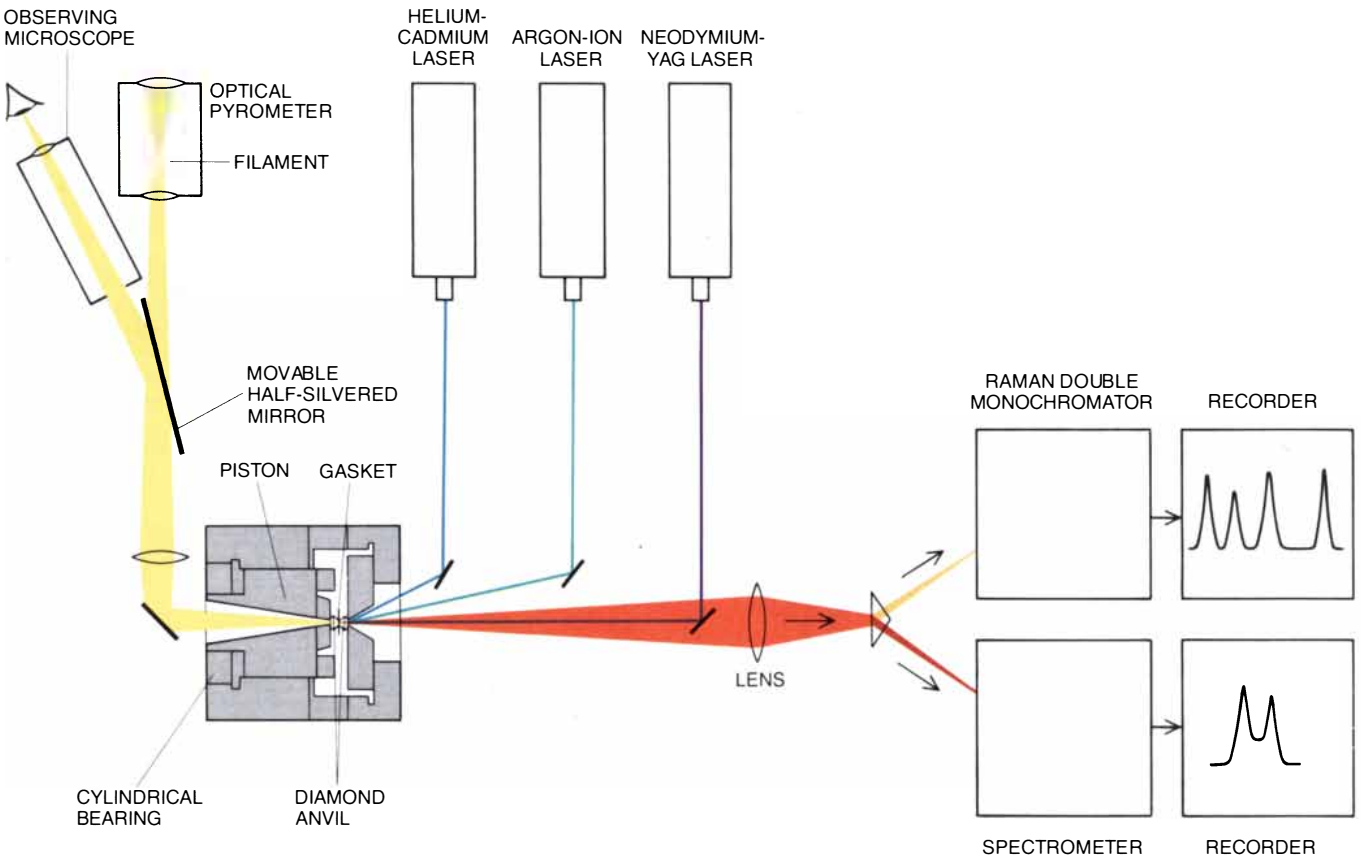
SOLID-PHASE CHANGE in a crystal of samarium monosulfide (SmS) gives rise to a spectacular color change and a change in the electrical properties of the crystal. In this photomicrograph made by the author the gold, high-pressure phase of the substance can be seen through one of the diamonds along the thrust axis of the diamond-anvil cell. Facets of the diamond, slightly out of focus because of the short depth of field in the photomicrograph, are also visible through the diamond. Samarium monosulfide is a dull black semiconductor at atmospheric pressure; the valence electronic energy band, or in other words the most energetic band populated by electrons in the material, is completely filled and the next-higher energy band is empty. Between the two bands there is also a sharp level of energy populated by electrons. At a pressure of 7,000 atmospheres the black color changes to gold because the electrons in the sharp level are squeezed into the empty band of energy, and the material begins to conduct electric current like a metal. The gold phase reverts to the black phase when the pressure is released.

the microscope. In 1970 a spectacular visual transition was discovered for the compound samarium monosulfide (SmS). At atmospheric pressure the substance is a dull black semiconductor: a material whose electrical conductivity is between that of a metal and that of an insulator. As the pressure is increased to 7,000 atmospheres, however, samarium monosulfide begins to glitter like gold, and the material conducts an electric current with the low resistance of a metal. If the pressure is subsequently reduced, the dull black semiconductor reappears; the colors of the sample viewed in the microscope blink back and forth between black and gold with a turn of a screw on the diamond-anvil cell.

The changes in color and electrical conductivity in samarium monosulfide are the result of a phase transition induced by pressure in the material. The most familiar phases of a substance are the solid, the liquid and the gas, but in most substances there are many distinct solid phases as well. A stable solid phase, or for that matter any stable phase of a system, is said to be in thermodynamic equilibrium with its environment. After prolonged contact with the surrounding temperature and pressure, the total energy (that is, the sum of the kinetic energy and the potential energy) stored by a substance must attain a minimum value. The total energy of a solid can be reduced by a change in the configuration of the atoms that make up the solid or by a change in the energy structure of the electrons in the solid. Therefore when the volume of a solid is reduced by compression, its atomic or electronic structure may have to change in order for it to reach energetic equilibrium with its new environment. Such changes can substantially alter the physical properties of the solid. For the student of high-pressure physics the discovery of a phase transition induced by pressure is a profoundly rewarding experience.

One of the most stimulating predictions in the theory of solids is that at pressures of from a million to several hundred million atmospheres many substances that are gases at room temperature and atmospheric pressure become metallic solids. For example, it is believed that hydrogen becomes metallic at about two million atmospheres and that helium becomes metallic near 110 million atmospheres. Although such high static pressures have not been reached, the diamond-anvil cell makes it possible to test the theory on which these predictions are based in more accessible experimental conditions.

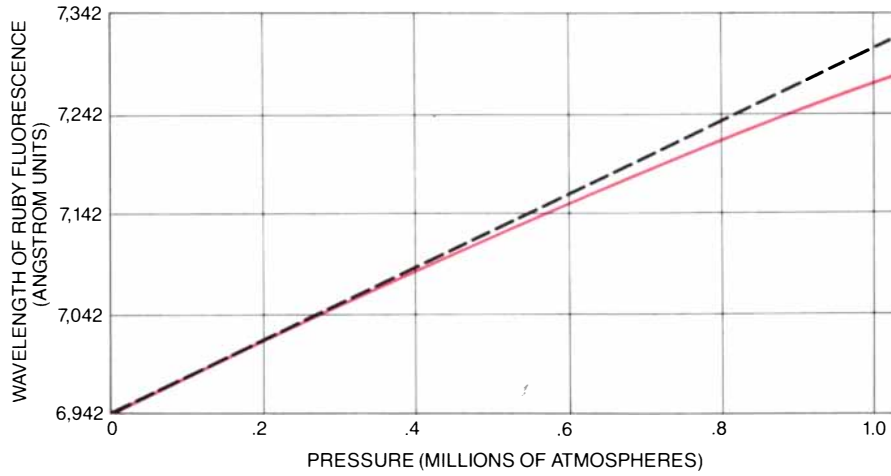
Whether or not a solid is metallic is determined by the energy-band structure of its electrons. In the isolated atom the electrons occupy discrete energy levels, but when many atoms are packed together in a solid, these levels broaden into bands of energy. The broadening is a quantum-mechanical effect: it comes about because two electrons that occupy the same energy level in two widely separated atoms must



TRANSPARENCY OF DIAMOND allows fine optical measurements to be made on the properties of a sample material confined at high pressures in the diamond-anvil cell. The composite experimental apparatus in the schematic diagram illustrates some of the measurements that can be carried out. The pressure is determined by focusing the beam of a helium-cadmium laser (*blue*) onto a ruby in the cell, thereby causing the ruby to fluoresce (*red*). A spectrometer measures the shift in the wavelength of the ruby fluorescence with pressure, and the shift gives the pressure in the cell. The beam of an argon-ion laser (*green*) can be focused on the sample, and the sample responds by giving off the light called Raman scattering (*yellow*), which is at a frequency lower than that of the incident green light. The coincidence in space of the red and yellow emissions is shown in orange. Analysis of the Raman-scattered light with the double monochromator (a spectrometer of very high resolution) makes it possible to determine the vibrational frequency of interatomic bonds and thereby measure the strength of the bonds under various pressures. Finally, the sample can be heated to about 2,000 degrees Celsius by a beam (*purple*) generated by a third laser, the neodymium-YAG (yttrium-aluminum-garnet) laser. The temperature is measured with an optical pyrometer, a device in which the incandescent color of the heated sample is visibly matched with the color of a glowing lamp filament of known temperature. The sample can thus be studied at the high temperatures and pressures found deep within the earth.

assume slightly different energy levels when they are confined to a small volume. The electronic energy bands in a solid are therefore made up of many, perhaps 10^{23}, discrete energy levels, but the levels are packed so tightly together that they cannot be resolved. Adjacent energy bands in a solid can overlap or can be separated by a gap, which represents a range of energy values "forbidden" to the electrons in the solid.

If the most energetic electrons in a solid fill one of the energy bands completely, and if there is a gap between the filled band and the next-higher band in energy, the solid is an electrical insulator. On the other hand, if the band of highest energy is only partially filled, or if it is empty and nonetheless overlaps with a fully occupied band, the solid is metallic and will readily conduct electric current. The basic theoretical prediction is that the band gap leading to electrical insulation in a solid can be narrowed at high pressures and finally squeezed shut. After the energy threshold of the empty energy band crosses the boundary of the filled band a sufficient condition for metallic conduction is met, and the insulator should become metallic. Calculations like those done for hydrogen and helium indicate that this event should take place in certain other materials at pressures accessible with the diamond-anvil cell. In xenon, for example, the metallic transition is expected at about 1.3 million atmospheres, and in molecular iodine it is expected at 200,000 atmospheres.



CALIBRATION OF PRESSURE in the high-pressure cell is based on the variation of the wavelength of ruby fluorescence with pressure. An increase in pressure gives rise to a proportional increase in the wavelength for pressures of up to 300,000 atmospheres (*solid curve in color*). For higher pressures there is a small deviation from proportionality (*broken line in black*). The scale was developed by J. Dean Barnett, Stanley Block and Gasper J. Piermarini of the Bureau of Standards and by Ho-kwang Mao and Peter M. Bell of the Geophysical Laboratory.

Solid xenon is an electrical insulator. The energy difference across the band gap associated with its properties as an insulator is quite high: nine electron volts at atmospheric pressure. The wide band gap also makes solid xenon transparent to light. Photons of light are absorbed by an insulator only if they are energetic enough to promote an electron across the band gap; photon absorption at lower energy would require an electron to occupy the forbidden band gap, which is impossible. The energy of the most energetic photons of visible light, however, is only about three electron volts, a third that of the band gap in xenon. The narrowing of the band gap, a prerequisite for the transition from an insulator to a metal, should therefore be visible in the diamond-anvil cell. The transparent, solid xenon at atmospheric pressure should become opaque to light as the pressure is increased.

Recent spectroscopic measurements of the absorption of light by solid xenon indicate that the energy across its band gap decreases to about four electron volts at a pressure of 600,000 atmospheres. This decrease in band-gap energy with pressure is in accord with the expected direction of change, but xenon remains a transparent insulator at 600,000 atmospheres. No one has yet seen solid xenon become opaque to light. In 1979, however, the electrical resistivity of a thin film of xenon was measured by compressing the film between a small, spherical diamond tip and a flat diamond face. The pressure on the xenon cannot be calibrated as precisely in such a device as it can be in the diamond-anvil cell, but for a pressure estimated to be more than 1.3 million atmospheres the resistivity of the xenon was quite low. It is likely, therefore, that the transition to the metallic phase has been observed in xenon, but further experimental corroboration is needed.

For iodine the transition from the insulating phase to the metallic one is established beyond doubt. At atmospheric pressure iodine is an electrically insulating crystal made up of diatomic iodine molecules. Two decades ago Harry G. Drickamer and his co-workers at the University of Illinois investigated the electrical resistance of iodine under pressure. They found a large, continuous decrease in the resistance as the pressure was increased to 200,000 atmospheres. On the basis of this result they suggested that solid iodine becomes metallic under pressure, but they were not able to show whether the metallic-iodine crystal is made up of atoms or of diatomic molecules.

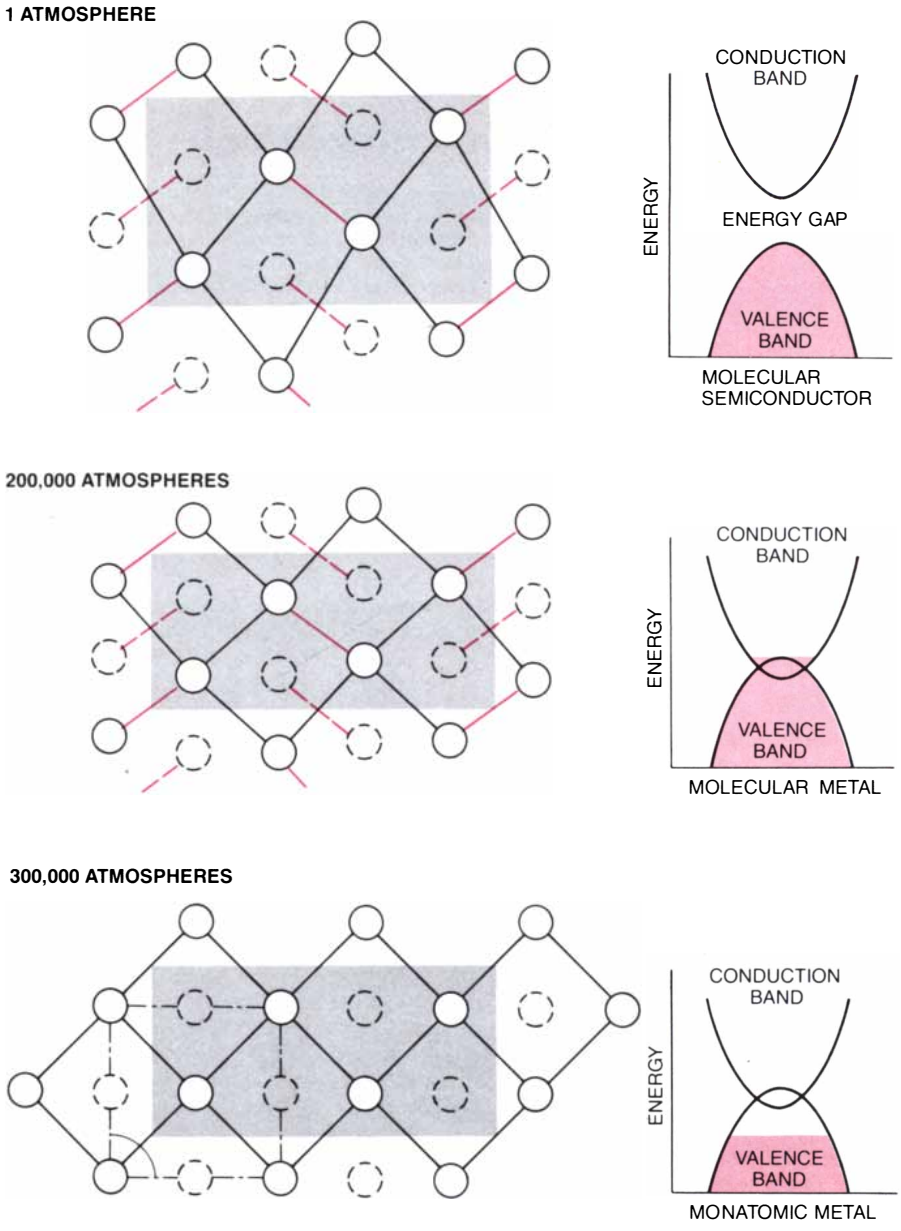
Only in recent years have high-pressure studies with the diamond-anvil cell settled the question. Since diamond is transparent to X rays, the atomic structure of materials under pressure in the cell can be investigated by the method of X-ray diffraction. The pattern of X rays reflected by the atomic lattice of a material makes it possible to deduce the structure and configuration of the lattice. It has now become clear through studies of X-ray-diffraction patterns that iodine gradually becomes metallic in the molecular crystalline form because a filled electronic energy band and an empty band begin to overlap. At a pressure of about 210,000 atmospheres, however, the molecular crystal is abruptly transformed into a monatomic one, and the structure of the electronic bands is entirely changed. The crystal remains metallic in its monatomic phase, but the high electrical conductivity in that phase is the effect of a partially filled band rather than the effect of two overlapping bands.

The three stages in the metallic phase transformation of iodine have become important for experimental studies in the behavior of solid hydrogen. There is considerable incentive to produce metallic hydrogen because it is predicted on theoretical grounds that metallic hydrogen would be superconducting at relatively high temperatures; in other words, it would conduct electric current without resistance at temperatures significantly above those required for other materials to become superconducting. Moreover, the interior of the giant planets Jupiter, Saturn, Uranus and Neptune is believed to consist largely of hydrogen. An understanding of the properties of hydrogen at high pressure is therefore important for the study of the planets.

At room temperature molecular hydrogen condenses to form a clear, electrically insulating and highly compressible solid near a pressure of 57,000 atmospheres. The solid is a molecular crystal because its fundamental unit is the diatomic hydrogen molecule (H_2). One of the most active questions in the current study of solid hydrogen is raised by the analogy with the metallic transition in solid, molecular iodine: Does hydrogen follow iodine and become me-

tallic by dissociating into a monatomic lattice, or does it remain in the molecular form and become metallic through the overlapping of two energy bands?

Two groups of investigators have pioneered the study of hydrogen and its isotope deuterium at high pressures. At the Geophysical Laboratory of the Carnegie Institution of Washington the strength of the bond in molecular hydrogen and molecular deuterium (heavy hydrogen, or hydrogen 2) has been determined at various pressures by Raman spectroscopy. The spectroscopic technique, named for the Indian physicist C. V. Raman, depends on the measurement of the frequency of light scattered by a sample under high pressures; hence the measurement could not be done if it were not for the transparency of the diamonds that confine the sample in the diamond-anvil cell. The strength of a molecular bond can be likened to the stiffness of a coil spring, and the stiffness of a spring gives rise to a characteristic frequency at which the spring vibrates by stretching and compressing. The strength of the molecular bond between two atoms can therefore be determined by measuring the vibrational frequency of the bond.



STRUCTURE OF IODINE is shown at three different pressures. The configuration of the iodine atoms in the crystalline solid is shown at the left and the corresponding electronic energy structure is shown at the right. At atmospheric pressure the basic unit of the crystal is the diatomic molecule (I_2); the solid is a semiconductor because there is a gap between the valence band, which is filled with electrons (*color*), and the conduction band, which is empty. As the pressure is increased to 200,000 atmospheres the molecules assume a more orderly, tightly packed configuration and the gap between the bands narrows until the bands overlap. The molecular crystal becomes an electrically conducting metal. At about 210,000 atmospheres there is an abrupt transition to an atomic, metallic phase; at 300,000 atmospheres the atoms in this phase form a highly regular crystal and the valence band becomes partially filled, like the most energetic energy band in an ordinary metal. Atoms and bonds in the plane of the paper are shown as solid circles and lines; atoms and bonds not in the plane of the paper are shown as broken circles and lines. Intramolecular bonds are shown in color and other bonds between atoms are shown in black. The high-pressure structures of iodine were determined by K. S. Takemura, S. Minomura, O. Shimomura and Y. Fujii of the Institute for Solid State Physics in Tokyo.

In order to carry out the measurement an intense beam of high-frequency blue light emitted by a laser is focused on the pressurized sample in the diamond-anvil cell. The blue light interacts with the vibrational state of the molecules in the sample and appears as scattered green light, which has a lower frequency than blue light. The difference between the frequency of the blue light and that of the green light is exactly equal to the vibrational frequency of the molecular bond. Hence by measuring the frequency of the scattered light with a spectrometer the vibrational frequency of the bond can be inferred. The shift of the incident light to a lower frequency is called the Raman shift.

The investigators at the Geophysical Laboratory have found that at 300,000 atmospheres the vibrational frequency of the interatomic bond in molecular hydrogen begins to decrease; in molecular deuterium the frequency begins to decrease at a pressure of more than 400,000 atmospheres. These findings show that the strength of the bonds is decreasing at such pressures, and the bonds continue to weaken up to at least 700,000 atmospheres. Hence it seems likely that under additional pressure the crystal of molecular hydrogen will eventually become monatomic; the transformation of hydrogen into a metal may well go through the same stages as the transformation of iodine does.

At the University of Amsterdam a second group has studied the change in the volume of solid, molecular hydrogen with increases in pressure. Until recently the compressibility of hydrogen had been determined experimentally only for pressures of up to 20,000 atmospheres, but Isaac F. Silvera and his co-workers have extended the range of known behavior to 370,000 atmospheres. Their method is simple and direct. The ruby for pressure calibration is placed in the hole in the gasket and the rest of the hole is filled with hydrogen. For each increment in pressure the diameter of the hole is measured under a microscope and the thickness of the hole is determined from the interference patterns of the light observable through the hole. Since the pressure is known from the shift in the ruby fluorescence spectrum and the change in the volume of the ruby is known on independent grounds, the volume of the hydrogen

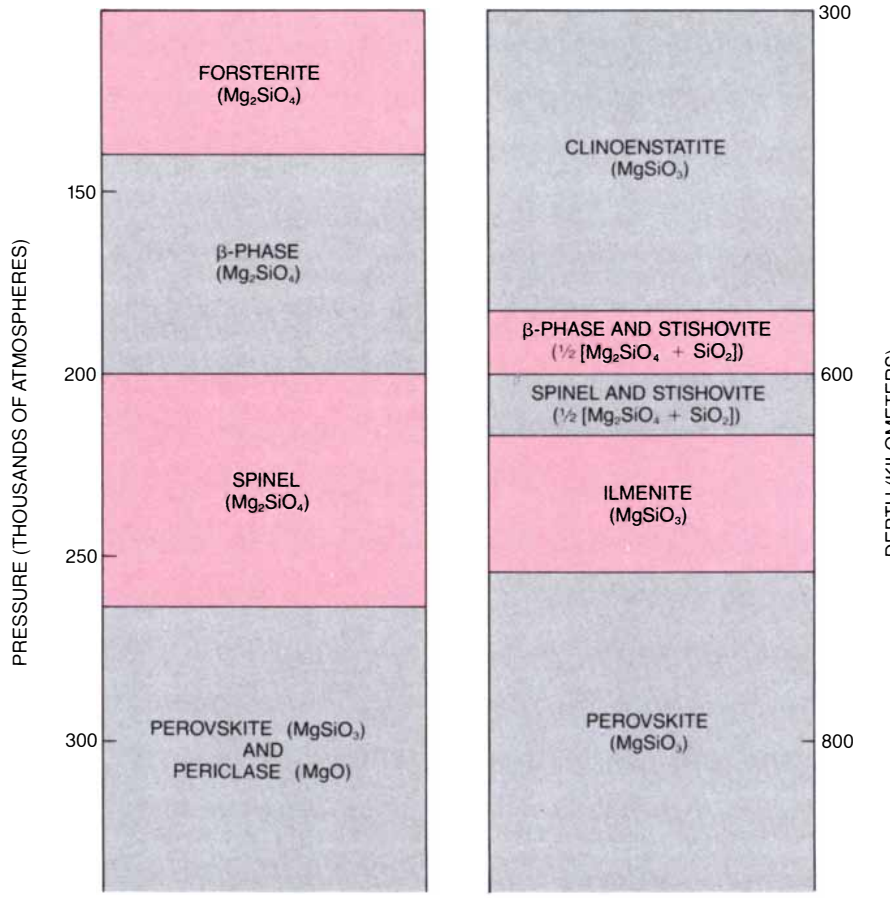
that fills the remainder of the cell can be plotted against pressure.

Silvera's results are corroborated by an entirely different measure of the change in volume with pressure that has been carried out at the Geophysical Laboratory. At any temperature above absolute zero part of the thermal energy of a solid is carried by sound waves, or periodic waves of compression and rarefaction of matter that propagate in all directions through the solid. It is possible to measure the velocities of these sound waves by the highly sensitive method of Brillouin scattering spectroscopy, named for the French physicist Louis Marcel Brillouin. Like Raman spectroscopy, Brillouin scattering spectroscopy conducted on samples at high pressures depends on the transparency of the container for the sample, and so once again only the diamond-anvil cell makes the work feasible.

Monochromatic laser light is focused on the sample of solid hydrogen, and part of the light is reflected in all directions by the sound waves in the sample. Along any given direction the frequency of the reflected beam of light is changed by the motion of the sound wave from which it is reflected: the distance between successive crests of the reflected light wave increases if the sound wave is moving away from the incident beam and the distance decreases if the sound wave is moving toward the incident beam. The phenomenon is the well-known Doppler effect. The velocity of a sound wave in a solid medium depends on the density of the medium. Therefore by measuring the shift in the frequency of the light that is reflected by the sample of pressurized hydrogen the density of the solid hydrogen at the applied pressure can be calculated. It is then a straightforward matter to determine the volume of the hydrogen from its density.

The new data from the two groups of experimenters make it possible to extrapolate the pressure for the transition to the metallic phase of hydrogen with greater confidence than ever before. The best estimates suggest the transition should come at pressures of between two and six million atmospheres, depending on correction factors that play a role in the calculations. It is not yet known whether the transition can be observed in the diamond-anvil cell.

Among the most important applications of studies done with the diamond-anvil cell are those in the geophysical and planetary sciences. To the experimentalist, who must be content with nearly microscopic samples of material under high pressure, it is ironic that below us there is a giant high-pressure laboratory. Inside the earth and the other planets both pressure and temperature increase with depth, and at the center of



STRUCTURE OF THE UPPER MANTLE of the earth, which extends from the base of the earth's crust to a depth of about 670 kilometers, has been studied experimentally by coupling a diamond-anvil cell with a laser for heating the material in the cell. Phase transitions for forsterite, a component of the rock olivine, and clinoenstatite, a member of the pyroxene group of minerals, are plotted with depth and the corresponding pressure within the earth. The names spinel, perovskite and ilmenite only denote crystalline structures; they refer to minerals having the same chemical composition as forsterite and clinoenstatite and the same crystallographic form as the minerals found on the earth's surface that usually bear those names. The sequence of phase transitions shown is based on investigations by Lin-gun Liu of the Australian National University. Although forsterite and clinoenstatite are two of the most abundant minerals in the mantle, the presence of oxides of iron, aluminum and calcium probably shifts the transition boundaries and may give rise to additional high-pressure phases. The composition of the lower mantle, from a depth of about 670 kilometers to the core-mantle boundary at 2,900 kilometers, is not known, but it is often assumed to be the same as that of the upper mantle.

the earth the pressure is four million atmospheres and the temperature is 4,000 degrees C. Basic to an understanding of the origin and dynamics of any planet is a detailed understanding of changes in the density, phase and chemical composition of the planet with depth, and all these factors are affected by changes in pressure and temperature. It is now well accepted, primarily on the basis of seismic data, that the interior of the earth is differentiated into a core, a mantle and a crust. What one would like, however, is to simulate the conditions of pressure and temperature at various depths in a planet, in order to directly observe their effects on the substances of which the planet is thought to consist.

Before the advent of the diamond-anvil cell such direct studies were possible only for conditions of pressure and temperature that correspond to a depth of about 400 kilometers. Difficulties were encountered not only in simulating higher pressures but also in heating the pressurized materials to a preselected temperature. The transparency of diamond has been exploited to circumvent the problem of heating. At the University of Rochester, Li-chung Ming and William A. Bassett showed that by focusing the beam of an yttrium-aluminum-garnet (YAG) laser through a diamond and onto the sample, the sample can be heated quickly to about 2,000 degrees C. The temperature can be measured by observing the color of the heated sample. In the hands of the geophysicist, therefore, the diamond-anvil cell has become a window on the earth's interior for conditions corresponding to those as deep as the boundary between the mantle and the core, 2,900 kilometers down.

A basic finding is that silicate minerals

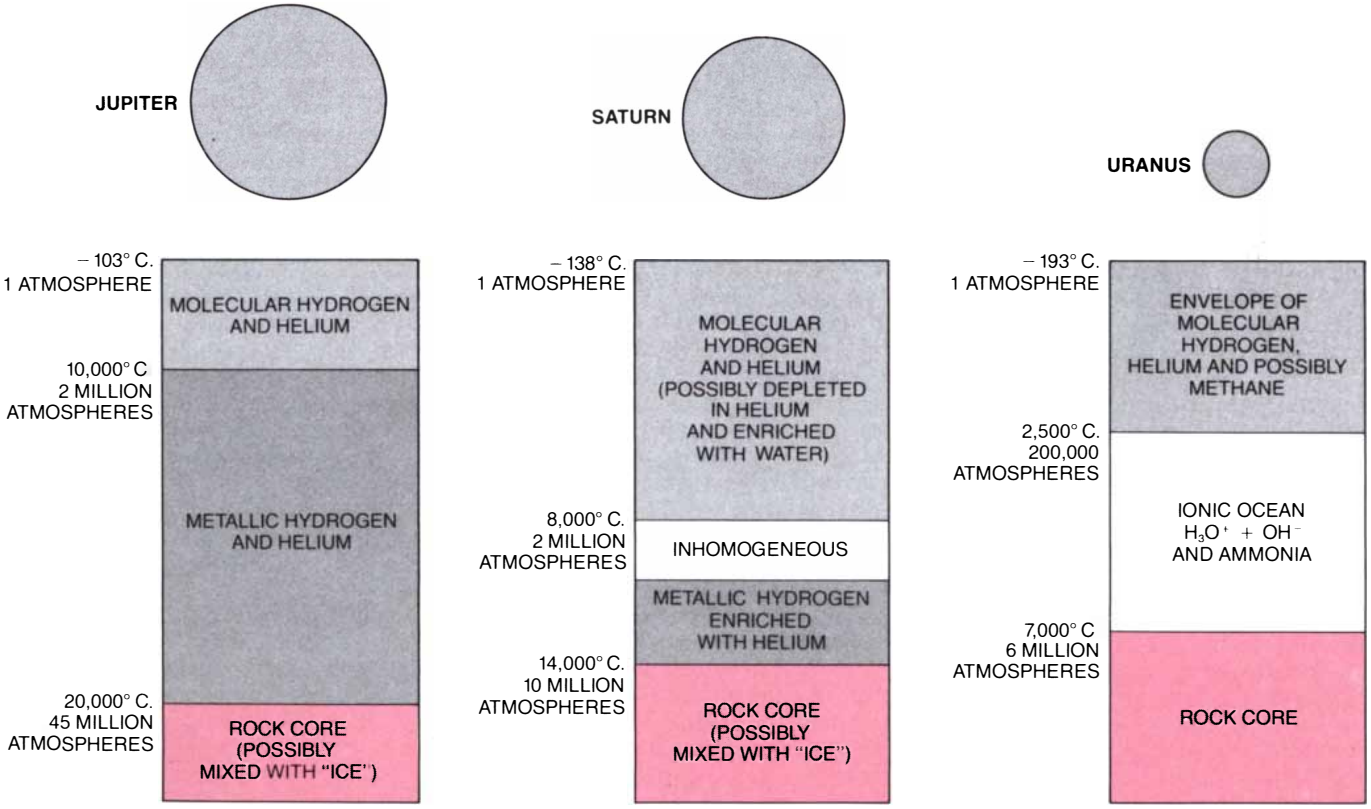
made up of silicon dioxide (SiO_2), magnesium oxide (MgO), aluminum oxide (Al_2O_3) and iron oxide (FeO) undergo a series of phase changes induced by pressure. Each change in phase causes a change in density, and the density changes can be correlated with the observed changes in the velocity of seismic waves with depth. Two major phase transitions have been correlated with seismic data. A sudden increase in seismic-wave velocity at a depth of about 400 kilometers is thought to be caused by a phase change in the magnesium and iron silicate olivine [$(Mg,Fe)_2SiO_4$] to the denser structure called spinel. Similarly, an increase in seismic-wave velocity at a depth of 670 kilometers is associated with a change from spinel to the structure known as perovskite. The perovskite phase appears to be stable, and it is believed to dominate the entire lower mantle. There are other anomalies in the seismic velocities that are also probably caused by phase changes. Such changes could be induced by less abundant silicate minerals that include calcium oxide (CaO) or aluminum oxide.

The conditions prevailing in the bulk of the matter of the giant planets have not yet become accessible to direct simulation with the diamond-anvil cell. At the center of Jupiter, for example, the pressure is estimated to be about 45 million atmospheres, and at the center of Saturn it is probably 10 million atmospheres; both are an order of magnitude greater than the highest pressure recorded so far with the diamond-anvil cell. Nevertheless, high-pressure experiments with materials such as hydrogen make it possible to build more plausible theoretical models of the composition and dynamics of the planetary interiors.

Hydrogen is thought to be the dominant material in both Jupiter and Saturn, and it is assumed to be present in its metallic form at depths below the depth corresponding to the pressure of the metallic-phase transition. At the core of the two planets there may be mineral oxides of magnesium, silicon and iron and also three kinds of "ice": solid ammonia, solid methane and ordinary ice. The ices are probably only minor constituents in Jupiter and Saturn, but they are thought to be significant in the core of both Uranus and Neptune.

In this context a natural question arises. What is the highest pressure that can be reached with the diamond-anvil cell? One limit would be imposed by a phase transition in diamond itself, perhaps to a metallic phase. A recent calculation by Mingtang Yin and Marvin L. Cohen of the University of California at Berkeley shows that the diamond structure does not collapse to any of the several well-known metallic crystal structures at pressures of less than 23 million atmospheres. Moreover, it is conservatively estimated that diamond is stable against any other metallic-phase transition up to pressures of at least 10 million atmospheres. Unfortunately diamond is likely to yield to plastic deformation at pressures below the metallic-phase transition, and so the ultimate pressure that can be reached with the diamond-anvil cell will probably be determined by the yield strength.

From plasticity theory it is known that the yield strength of diamond is greatest over regions where the crystalline structure is perfect. For example, it is estimated that in a perfect diamond pressures of up to five million atmospheres might be attained before the diamond begins to yield. The smaller the region of a diamond that must bear the highest pressures, the greater the chance that the region has a perfect crystalline structure. Hence it appears that the way to achieve higher pressures is to conduct experiments on a progressively miniaturized scale. It is amusing to note that the benefits of miniaturization, so familiar in electronics, may make it possible to project the investigator to much higher pressures inside the largest and most massive objects in the universe.



INTERNAL COMPOSITION of three giant planets is inferred from theoretical calculations based whenever possible on the extrapolation of experimental results. Investigations of solid iodine at high pressures suggest that solid molecular hydrogen should undergo similar phase transitions and become a conducting metal at a pressure of between two and six million atmospheres. It is therefore assumed that at the depths inside the planets corresponding to such pressures hydrogen is found in a metallic form. The additional differentiation of planetary structures is based on spectroscopic studies and on theoretical extrapolations. The "ices" at the core of Jupiter and Saturn are solid ammonia, solid methane and ordinary ice. The models were devised by David J. Stevenson of the California Institute of Technology.

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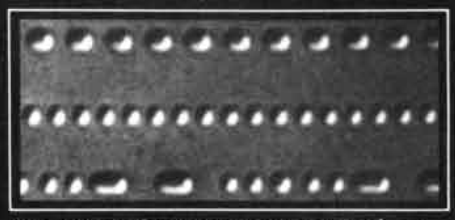

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Its 104.9-inch wheelbase, its 14½-foot length and its under 2,700 lb. weight help define the 190 Class as a new equation of space and mass and energy—the trimmest and lightest Mercedes-Benz sedan of the modern era.

Its new multilink independent rear suspension meanwhile defines the term "breakthrough." Each rear wheel is precisely located by five individual links, positioned according to the principles of *spatial kinematics* and meant to maintain each wheel constantly in an ideal relationship to the road.

Rear wheel "steering" tendencies are thus eliminated. "That means the back goes where *you* want it to go," explains one automotive journalist, "instead of where *it* wants to go. That, in turn, means better handling at no sacrifice in ride."

Small wonder that *Road & Track* has ventured the opinion that the new 190 Class "will challenge some of the finest sports sedans in the world on just about any road you choose."

The praise might be taken further yet. Of all the superbly roadworthy production cars Mercedes-Benz has ever built, this may be the most superbly roadworthy of all. As one quick run down a stretch of winding road can prove, far more eloquently than words.

ALMOST A RACING ENGINE

With its cross-flow cylinder head, hemispherical combustion chambers and overhead camshaft, the 190E's new 2.3-liter four-cylinder gasoline engine might almost be taken for a pure racing design. Nothing about its smoothness or torque suggests the typical four—nor does its test-track maximum of 115 mph-plus. Controlling it is an innovative fuel injection system *combining* the wizardry of electronics with the simplicity of a mechanical operation; Mercedes-Benz steals a march on the industry again.

The 190D 2.2 Sedan not only introduces a brand-new four-cylinder diesel engine, but places it in new surroundings: *encapsulated* within sound-deadening paneling, even underneath. Factory tests reveal a drop in noise emissions of five decibels.

You can choose between five-speed manual and four-speed automatic versions of either model. Both are designed for quick shifting and spirited driving. The new hydraulically controlled torque-converter automatic, with its tunnel-mounted lever, can be flicked through the gears in manual fashion whenever you choose.

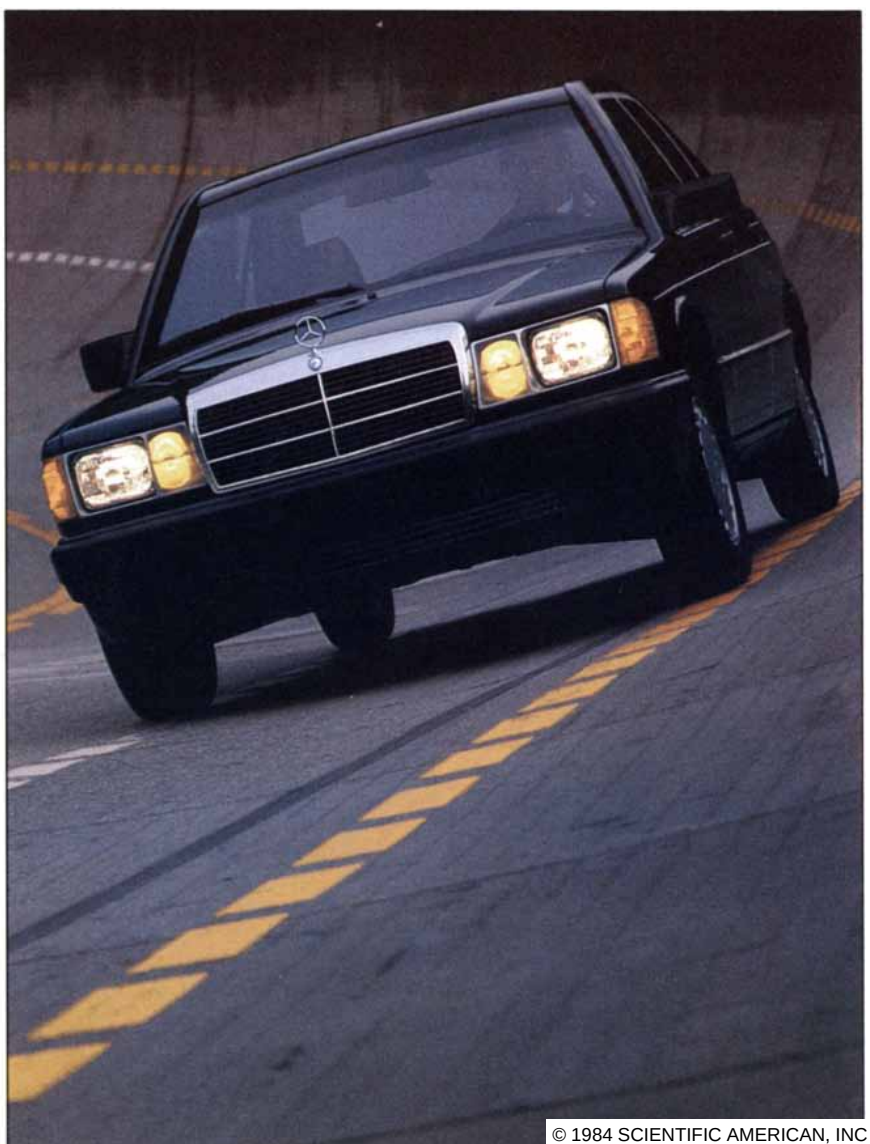
One of the key functional advances of the new 190 Class is its shape. It emerged not from a styling salon but from nine cumulative

*Approximate suggested advertised delivered price at port of entry.

to do it with the poise, the comfort and the smoothness that help make a Mercedes-Benz a Mercedes-Benz.

months of wind tunnel tuning, and emerged with a 0.35 coefficient of aerodynamic drag–for comparison, within .01 of the sleek new two-seater Chevrolet Corvette. Even the forged light-alloy wheels play their aerodynamic part. They are flat, smooth, wind-cheating discs.

The 190 Class performs with all the brio of what is called a sports sedan, but, in truth, it is too versatile and practical a design to be one. Into that 14½-foot wedge have been cut four wide-opening doors. Inside is provided passenger space for five. There is even a large (i.e., 11.7 cubic foot) trunk. Inducements enough for the sports sedan aficionado to graduate at last to a Mercedes-Benz.



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Your $24,000 brings you, among other things, an exhaustive list of amenities and conveniences as standard equipment. Even the electric sliding roof is a non-extra-cost option in the 190 Class.

Wind noise is suppressed to near silence at highway speeds by aerodynamic design and by scrupulous fitting of every door and window. A *second* firewall between the engine and passenger compartment serves to help muffle engine noise. Rattling and squeaking sounds are obviated by welding of the body and chassis into a rigid, single structural unit. Road rumble from beneath is soaked up by a 39-lb. blanket of plasticized undercoat.

The new 190 Class represents the most extensive research and development effort in the history of Mercedes-Benz. What has resulted from that decade of technological exploration and refinement ranks as one of the most remarkable automobiles in the history of Mercedes-Benz.

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SCIENCE AND THE CITIZEN

Action, Reaction

One of the main sticking points in bilateral arms-control negotiations between the U.S. and the U.S.S.R. for almost a decade has been the issue of cruise missiles. Disagreement on how to assess the likely impact of these versatile jet-propelled weapons on the existing balance of military power was a major cause of the impasse that prolonged the second round of the strategic-arms-limitation talks (SALT II). Because of the difficulty in distinguishing reliably between modern strategic, or long-range, cruise missiles and various shorter-range versions of the same basic weapon system, the Russian negotiators insisted initially on including in the numerical SALT II quotas for strategic delivery systems all cruise missiles potentially capable of long-range missions ("long range" in this context being defined as more than 600 kilometers). The U.S., which at the time was generally believed to hold a substantial lead in advanced cruise-missile technology, opposed any such provision, reportedly because it would prevent the planned deployment of U.S. intermediate-range cruise missiles without placing any compensating restriction on Russian intermediate-range ballistic missiles.

In the end the two sides agreed to a complex compromise that in effect limited the number of long-range air-launched cruise missiles (ALCM's) by counting the number of bombers assigned to carry them; at the same time the U.S.S.R., in another major concession to the U.S. position, agreed to postpone action on any comparable curbs for ground-launched cruise missiles (GLCM's) or sea-launched cruise missiles (SLCM's), pending further negotiations. The subsequent refusal by the U.S. Senate to ratify the SALT II Treaty has placed even the partial ALCM restraints in some doubt.

Since then the U.S. has vigorously exploited its advantage in cruise-missile technology, which has been estimated to amount to a head start of between five and 10 years. ALCM's armed with nuclear warheads are now being installed on B-52 bombers stationed in the U.S., and with the apparent failure of the bilateral talks on intermediate-range weapons in Europe the first contingents of nuclear-armed U.S. GLCM's have begun to arrive in several Western European countries. The U.S. is also proceeding at an accelerated pace with the development and testing of an assortment of SLCM's, both nuclear and non-nuclear, for service on submarines and surface warships.

Meanwhile the U.S.S.R., which had consistently called for a total ban on long-range cruise missiles at both the SALT and the START sessions, has apparently made a considerable effort to close the gap in advanced cruise-missile technology. According to *Soviet Military Power 1983,* a publication of the U.S. Department of Defense, "the U.S.S.R. has begun test flights of a new generation of ground-, sea- and air-launched cruise missiles, missiles with nuclear capability with ranges in excess of 1,600 kilometers, significantly expanding the flexibility of Soviet strategic options." A more recent, unattributed report, published in *Aviation Week & Space Technology,* suggests that the new Russian long-range cruise missiles ("scheduled for deployment starting in 1985") are equipped with an extremely accurate, active guidance system similar to the terrain-contour-matching radar installed in the current generation of U.S. GLCM's and SLCM's. The rapid development of the advanced guidance technology by the U.S.S.R. is said to have taken the U.S. military-intelligence community "by surprise."

Prominently listed among the new Russian long-range cruise missiles is a submarine-launched version U.S. officials refer to as the SS-NX-21. "With an estimated maximum range on the order of 3,000 kilometers," the official Department of Defense publication reports, "its mission is primarily nuclear strike." The new SLCM has figured in recent speculation about what the Russians mean when they say they will counter the U.S. deployment in Europe of intermediate-range missiles capable of reaching the U.S.S.R. by deploying "comparable" weapons capable of hitting targets in the U.S. Launched from the torpedo tubes of submerged submarines off the U.S. coast, cruise missiles such as the SS-NX-21 would presumably give little warning of an attack.

The expected deployment of the new generation of Russian cruise missiles has already led to renewed calls for the upgrading of the North American air-defense system, which is not now considered seriously threatened by the comparatively ineffective Russian strategic-bomber force. According to an unnamed U.S. official quoted in *Aviation Week,* the projected Russian "cruise-missile threat" will be "a major factor in the overall strategic defense plan," requiring more capable interceptor aircraft, improved over-the-horizon-backscatter (OTH-B) radar systems and additional airborne-warning-and-control-system (AWACS) aircraft. The cost of the radar improvements alone is estimated at "approximately $1 billion."

In many ways the entire cruise-missile episode is strikingly reminiscent of the advent of multiple independently targetable reentry vehicles (MIRV's) in the preceding decade. In both cases the U.S. initially resisted efforts to include in a major strategic-arms-control agreement a new military technology in which it held an apparent advantage, only to find that the U.S.S.R. quickly closed the technological gap, thereby placing the U.S. at greater risk of nuclear destruction than ever before and triggering the perceived need for enormously costly new defensive measures.

A Star Named George

In the 570 million years since the beginning of an abundant fossil record of the earth's biota almost every species has become extinct. Until recently the extinctions were thought to come at a roughly constant rate; the great biological crisis of 65 million years ago that resulted in the disappearance of the dinosaurs was thought to be one of a mere handful of exceptions to the hypothesis of continuity. Now a careful statistical analysis of the extinctions of more than 500 families of marine animals shows the dinosaur extinction to be less the exception than the rule. The analysis, conducted by David M. Raup and J. John Sepkoski, Jr., of the University of Chicago, shows that the rate of extinctions over the past 250 million years has increased systematically every 26 million years; the most recent ones were some 13 million years ago. The striking regularity of the extinctions suggests an extraterrestrial cause, and an astrophysical model that explains the regularity has now been proposed by Richard A. Muller and Marc Davis of the University of California at Berkeley and by Piet Hut of the Institute for Advanced Study. If the model is in accord with reality, it would bring about a fundamental revision in the understanding of the solar system.

According to Muller and his colleagues, the sun is a member of a binary-star system. The sun's companion is most likely a faint dwarf star, perhaps a tenth the mass of the sun, that is now at a distance of about 2.4 light-years. It would be straightforward to suppose the periodic extinctions were somehow caused by the passage of the companion through the solar system every 26 million years; indeed, one of Muller's initial hypotheses called for the companion to swing close enough to the sun to disturb the orbits of the asteroids between Mars and Jupiter and thereby subject the earth to an intensified planetoidal bombardment. That mechanism would not work, however, because an orbit with a 26-million-year period that pass-

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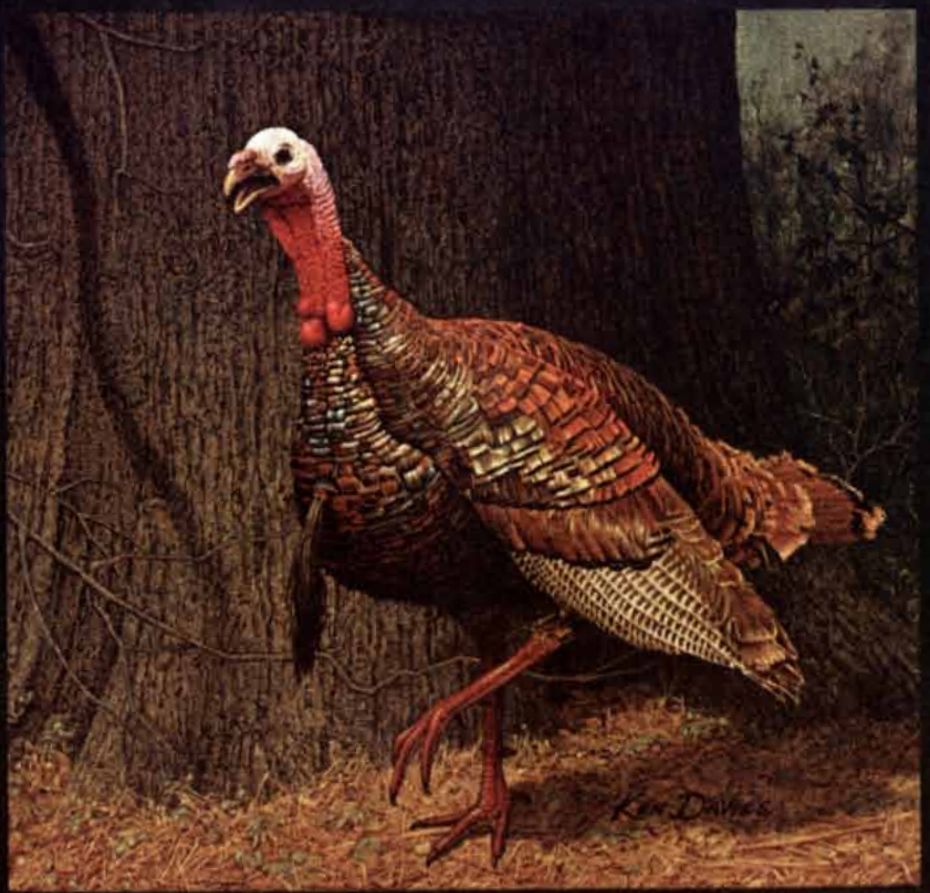

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es so close to the sun would not be stable. Gravitational perturbations would probably cause the companion to miss the sun by 100 astronomical units on its second orbit. (An astronomical unit is the mean distance between the earth and the sun.)

In December of last year, meeting with Davis and Hut on the problem for the first time, Muller explained the apparent failure of the binary-star hypothesis to account for the periodic extinctions. Hut remarked that the hypothesis might be saved if the companion star, instead of passing through the asteroid belt, were to pass through the Oort cloud. That cloud is a huge shell of interstellar debris, weakly bound by the sun's gravity, in which comets are thought to form; it is named for J. H. Oort of the University of Leiden. Oort pointed out in 1950 that the comets observed in the inner solar system can be accounted for by perturbations in the orbits of some 10^{11} comets found between 10,000 and 100,000 astronomical units from the sun. The perturbations are caused by the random passage of stars in the neighborhood of the solar system. The comets that reach the inner solar system from this region of the Oort cloud are either trapped in relatively small solar orbits or swing so rapidly around the sun that they eventually leave the solar system.

Davis and Hut recalled that in 1981 a revised estimate of the population of comets had been published by Jack G. Hills, then of the Jet Propulsion Laboratory of the California Institute of Technology. According to Hills, comets must be far more numerous in the inner part of the Oort cloud—1,000 to 10,000 astronomical units from the sun—than they are in the region of the cloud considered by Oort. In the inner Oort cloud Hills estimated that there are roughly 10^{13} comets, although their total mass is less than the mass of Jupiter. The comets in the inner cloud are sufficiently well bound by the sun's gravity not to be much perturbed by a passing star, but Hills calculated that once every 500 million years the random path of a nearby star would come close enough to the sun to cause such perturbations. The perturbations would have dramatic consequences for the earth. Roughly a billion comets would arrive in the region of the solar system inside the earth's orbit over a period of from 100,000 to a million years. Of these comets, Hills estimated, perhaps 10 to 200 would hit the earth.

Most comets are believed to consist largely of ices such as solid ammonia, solid methane and ordinary ice, but some may also have a rocky core. The impact of a rocky comet on the earth could be the source of a thin layer of clay, highly enriched in the element iridium, that has been found in geologic formations at several locations. The enriched layer of iridium was first noted by Luis W. Alvarez and his son Walter Alvarez of Berkeley and their associates; it coincides with the biological crisis of 65 million years ago, when roughly 70 percent of the families of organisms on the earth, or more than 90 percent of the species, became extinct.

Many geologists and paleontologists now accept the Alvarez hypothesis that the origin of the iridium was extraterrestrial and that the impact of the extraterrestrial object with the earth threw up enough dust to darken the earth's atmosphere for at least six months. The dust cut off much of the sunlight that normally reaches the earth's surface, inhibiting photosynthesis and causing the disruptions in the food web that led to the mass extinctions. The mechanism is similar to the one that, according to many atmospheric scientists, would give rise to a "nuclear winter" after a large-scale nuclear war.

If the cometary impacts proposed by Hills can account for the kind of extinctions suggested by the Alvarez group, Muller, Davis and Hut reason that a consistent explanation can be given for periodic extinctions. The sun's binary companion must pass close enough to the inner Oort cloud every 26 million years to cause a shower of comets in the vicinity of the earth. Following Hills's analysis, they calculate that a dwarf star passing within 30,000 astronomical units of the sun should cause an average of three or four comets to hit the earth in every orbital period of the star. The statistical variability inherent in this number can account for the fluctuations in the extinction rate that are observed in the geologic record. Moreover, the mechanism leads to the prediction that several cometary impacts can be associated with a single rise in the extinction rate. That prediction is partially confirmed by the finding that associated with the iridium layer are at least three distinct layers of microtektites. Tektites are the glassy stones believed to originate when a large object strikes the earth and splashes out melted silicate.

A few days after Muller and his colleagues had reached these conclusions Walter Alvarez suggested to Muller that periodic comet showers should be reflected in the periodic excavation of large craters on the earth. Muller and Alvarez have analyzed 13 impact craters larger than 10 kilometers across that have been accurately dated, and they find another striking regularity: the impacts come on the average every 28.4 million years. The most recent increase in the frequency of the impacts was 13.5 million years ago, which nearly coincides with the most recent increase in extinctions. The probability that the increases are caused by random events is less than five chances out of 1,000. Muller points out that the discrepancy between the 26-million-year period and the 28.4-million-year one can be absorbed by uncertainties in the dating of the extinctions.

The most important prediction of the model is, of course, the existence of the companion star. The model makes no prediction, however, about the position of the companion in the sky. Several investigators are now searching among roughly a million stars brighter than the 12th magnitude for stars that show a small proper motion against the background of more distant stars. If the companion is found, Muller and his colleagues suggest in a footnote to their account several names: "Nemesis, after the Greek goddess who relentlessly persecutes the excessively rich, proud and powerful... Kali, 'the black,' after the Hindu goddess of death and destruction, who nonetheless is infinitely generous and kind to those she loves; Indra, after the vedic god of storms and war, who uses a thunderbolt (comet?) to slay a serpent (dinosaur?), thereby releasing life-giving waters from the mountains, and finally George, after the saint who slew the dragon."

Low-Fertility Zone

It has often been said that the high level of fertility in the African countries south of the Sahara (and in other underdeveloped countries as well) is one of the main obstacles to their economic development. African cultures encourage couples to procreate, and in many parts of tropical Africa healthy women have an average of as many as 10 children by the time their childbearing years are over. In some parts of central Africa, however, a problem more serious than high fertility appears to be the inability to bear children. For example, in several districts of Zaire and the Central African Republic in the 1960's more than half of all young women were sterile before they had even had a child. Writing in *World Health Statistics Quarterly,* John C. Caldwell and Pat Caldwell of the Australian National University conclude that the infertility is caused by a long-lasting epidemic of gonorrhea, introduced when the area was opened up by colonizers in the 1870's.

The low-fertility zone in central Africa includes two areas in the modern states of Sudan, the Central African Republic, Zaire, Gabon and Cameroon. The population of the low-fertility zone is about 10 million. The two areas are close together but not contiguous; they are divided by a narrow strip where fertility is average for tropical Africa. African populations in which sterility is not widespread tend to have a total fertility rate of 6.5 or more. The total fertility rate is the number of children each woman would have on the average by the end of her reproductive span if the current level of fertility persisted. The

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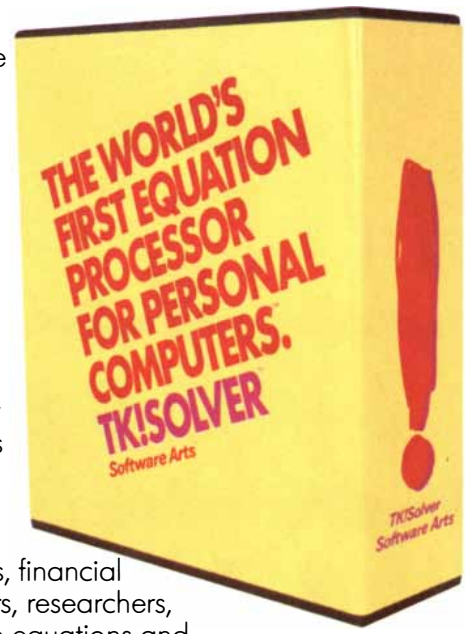

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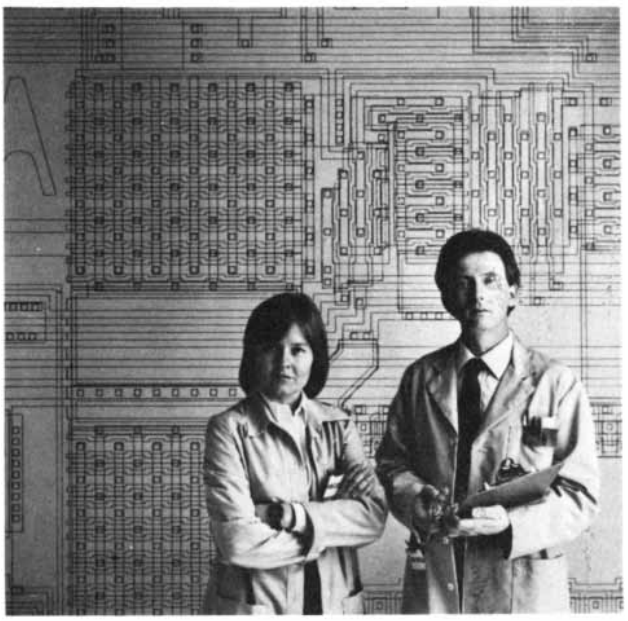

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people of the low-fertility zone have a total fertility rate of less than 5.

In some parts of the zone the decrease has been substantial indeed. During the late 1950's the total fertility rate in the Uele district of northern Zaire was about 3. The Caldwells write: "These are levels which suggest that pathological sterility has at least halved the potential number of births." The suggestion that fertility was reduced by half is confirmed by interviews with individual women in northern Zaire.

In the U.S. or the industrial nations of Western Europe such a level of childlessness among young women might be voluntary, but in central Africa this is clearly not the case. All the demographic surveys done in tropical Africa have found that both men and women want large families. A survey carried out by the Caldwells in the Nigerian city of Ibadan, not far from the low-fertility zone, showed that only 1 percent of women had voluntarily limited their families to fewer than six children. As recently as 1970 only 2 to 3 percent of married women in the coastal areas of French-speaking Africa were using contraceptives, and in the interior almost no married women were using them. In many African societies a woman is quickly divorced if the marriage is childless.

What involuntary factors accounted for the high frequency of childlessness? To answer the question the Caldwells drew on ethnographic, demographic and historical data. The ethnographic evidence included the fact that the regions of low fertility roughly coincide with the boundaries of societies that do not have strong cultural barriers against premarital and extramarital sexual intercourse. In such societies female sexual activity often begins at age 10 or younger and little emphasis is put on a woman's virginity at marriage. In addition, in many such societies it is customary for a wife to abstain from intercourse for as long as three years after the birth of a child, a custom that encourages extramarital intercourse by husbands.

The demographic data are drawn from surveys made in northern Zaire in the mid-1950's and again in the mid-1970's. Interviews with older women made it possible to reconstruct the record of fertility in the region since the late 19th century. The results suggest that the sterility rate was already about 10 percent in 1880. By 1900 it had begun to increase sharply, reaching a peak soon after World War II. In the 1950's infertility became less common among young women, only to become commoner after 1960.

The historical evidence is that the high-sterility region is part of the last area of Africa to have had sustained contact with the outside world. Although the coastal regions of East Africa and the West African savanna had long been visited by Arab traders and European colonizers, the interior was not opened up until the 1870's. The low-fertility zone is almost entirely within what was the Congo Free State and the French Congo, two of the last African colonial states to be established.

From such diverse data the Caldwells constructed the following explanation. The colonization of central Africa was accompanied by the introduction of strains of venereal disease that were unknown in the region. The inhabitants of the coast and the savanna, where contacts with Arabs and Europeans were common, had had centuries in which to build up immunologic resistance to foreign pathogens, but the natives of the interior were quite vulnerable. Syphilis and gonorrhea spread particularly fast in the societies with low barriers to premarital and extramarital intercourse. Gonorrhea can cause sterility if its symptoms remain untreated. In such societies young girls frequently have intercourse with adult men, hence the girls can become sterile before the age of marriage.

Even a single injection of penicillin

given in the course of a gonorrheal infection can prevent sterility. In the 1940's and 1950's much penicillin was administered by the Belgian authorities in the Congo to combat yaws and venereal disease. As a result the level of sterility decreased among young women but not among older ones, since the antibiotic cannot reverse the sterilizing effects of gonorrhea. When the Belgian health campaigns were interrupted by anticolonial rebellions and civil war in the 1960's, the level of sterility began to rise again. After political stability was achieved health programs were reintroduced and the proportion of childless women began to decrease. Nevertheless, the peoples of central Africa have paid for their contact with the outside world a high price in reproductive capacity.

Out of Control

Oncogenes cause cancer, but how do they do it? They are altered versions of normal genes that must themselves have a benign role in the life of normal cells; presumably an oncogene's effect is to mimic, in an inappropriate way, the action of those normal genes. The essence of cancer is the uncontrolled proliferation of cells. It has therefore seemed likely that at least some oncogenes act by inappropriately mimicking the activity of normal cellular growth factors. Results from several laboratories suggest that is the case.

Last summer groups headed by Russell F. Doolittle of the University of California at San Diego and by Michael D. Waterfield of the Imperial Cancer Research Fund in London reported finding close similarities between the amino acid sequence encoded by an oncogene called *sis* and one of the two chains of platelet-derived growth factor (PDGF), a substance that promotes cell division in wound healing. A few months later a group headed by Stuart A. Aaronson of the National Cancer Institute found structural and immunological similarities between the oncogene's protein product and PDGF. Recently the relation has been pinned down by Steven F. Josephs and his colleagues at the National Cancer Institute and by Aaronson's group. They determined the nucleotide sequence of the normal human version of *sis* and found that it encodes one chain of PDGF. It appears, in other words, that the oncogene encodes a growth factor that mimics PDGF's activity but does so inappropriately.

Now a link has been established between a different oncogene, *erb-B*, and a human growth factor called epidermal growth factor (EGF). The work is reported in *Nature* by Waterfield's group and the groups of Joseph Schlessinger at the Weizmann Institute of Science in Israel and Axel Ullrich at Genentech, Inc. They were studying not the growth factor itself but its receptor: a complex protein, implanted in the cell membrane, to which EGF binds, thus triggering a signal that promotes DNA synthesis and cell division. The receptor is composed of a number of distinct peptides, or short protein chains, 14 of which the investigators isolated. They found that six of the peptides have amino acid sequences that are very closely related to stretches of the sequence encoded by *erb-B*. The oncogene was isolated from a virus that causes leukemia in chickens. The suggestion is that an infecting virus must have picked up from a chicken, and incorporated into its own DNA, part of the chicken gene encoding the EGF receptor. There is evidence that the oncogene encodes the regions of the receptor embedded in the membrane and extending into the interior of the cell, and that it does not encode the outermost portion of the receptor, the region to which EGF binds.

Waterfield and his colleagues point out that the findings on PDGF and on EGF suggest there may be two different mechanisms whereby an oncogene can subvert the normal regulation of growth. In the case of *sis* the oncogene

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seems to encode a protein that simulates the activity of the growth factor itself. In contrast, *erb-B* seems to encode a faulty EGF receptor. Instead of transducing a growth-promoting signal appropriately, when EGF binds to it, the truncated receptor might continuously generate an equivalent signal on its own and so promote uncontrolled growth.

Dynamic Sister

Venus is often called the earth's sister planet because it is much like the earth in size and density and because it is the earth's nearest planetary neighbor. Just how similar is it geologically? Venus is thought to be heated, like the earth, by the decay of long-lived radioactive elements. On the earth this internal heat finds its principal outlet at midocean ridges, where hot magma wells up to form new oceanic crust. Whether the Venusian crust also consists of moving tectonic plates or whether, like the moon, Mercury and Mars, it is made up of a single, continuous plate is still uncertain. Several strands of evidence now suggest, however, that the dominant mode of heat transfer on Venus may be volcanoes, some of which are quite large and apparently still erupting.

Much of the evidence comes from the *Pioneer Venus* spacecraft, which has been orbiting the planet since December, 1978. Radar data from the spacecraft have allowed investigators to prepare a topographic map of nearly the entire surface and to image part of it as well. According to Harold Masursky of the U.S. Geological Survey, the mountainous areas of Beta Regio, Phoebe Regio and Atla Regio appear to be great fault zones lined by volcanoes.

The two main peaks in Beta Regio, for example, resemble terrestrial "shield" volcanoes such as Mauna Loa and Kilauea in Hawaii in that they are broad and gently sloping. Together the mountains of Beta Regio are nearly 1,300 miles in extent, far larger than the Hawaiian volcanoes; assuming they are indeed volcanoes, they may be the largest (in volume) in the solar system. Moreover, says Masursky, the radar images suggest that the Beta Regio peaks have been active recently: bright rays emanating from the peaks can be interpreted as evidence of young lava flows, since brightness on a radar image indicates a relatively rough, unweathered surface. No radiating streaks are visible around the smaller volcanolike structures of Atla Regio, but the sharp, conical shape of these two mountains suggests that they too may be young volcanoes.

The hypothesis is supported by an analysis of Venus' gravity field, which can be measured by tracking tiny perturbations in the orbit of *Pioneer Venus*. Beta Regio and Atla Regio are areas of anomalously high gravity: the satellite is drawn down slightly as it passes over them. On the earth positive gravity anomalies are associated with "hot spots" in the mantle, where magma is welling up toward the surface, and according to Masursky the largest deviations are found at very young volcanoes. The Venusian anomalies can be twice as large as terrestrial ones.

None of this proves, of course, that volcanoes on Venus are active. The Voyager spacecraft provided dramatic confirmation of volcanism on Jupiter's moon Io by photographing eruptions in progress, but that is not possible on Venus because a thick layer of sulfuric acid clouds hides the surface. The atmosphere itself, however, contains indirect evidence of volcanism in the form of abundant sulfur dioxide, which is oxidized under the influence of sunlight and then hydrated to form sulfuric acid. The abundance of sulfur dioxide is surprising, says Ronald G. Prinn of the Massachusetts Institute of Technology, because analysis of soil samples by the Russian landing craft *Venera 13* and *Venera 14* showed that the Venusian surface contains significant amounts of calcium, which reacts readily with sulfur dioxide and would thus tend to draw it out of the atmosphere. Since there is a sulfur "sink," Prinn argues, there must also be a source. The source could be direct injection of sulfur dioxide into the atmosphere by volcanic eruptions.

One such eruption may have taken place as recently as 1978, according to Larry W. Esposito of the University of Colorado at Boulder. The evidence comes from the *Pioneer Venus* ultraviolet spectrometer, which has been measuring the amount of sulfur dioxide in the atmosphere above the clouds (the clouds themselves are not transparent to ultraviolet) at an altitude of 70 kilometers. When *Pioneer Venus* went into orbit around the planet in 1978, Esposito and other investigators were surprised to find that the sulfur dioxide concentration was 50 times higher than the maximum level expected based on the fact that none had been detected from the earth. Since then, however, the concentration has declined by 90 percent.

This pattern suggests to Esposito that a huge volcanic eruption injected sulfur dioxide into the atmosphere not long before *Pioneer Venus* arrived at the planet. The sulfur dioxide has since been reacting photochemically to form sulfuric acid and gradually subsiding into the cloud layer. If this hypothesis is correct, one would expect to be able to observe sulfuric acid aerosols. A polarimeter (which measures light scattered off particles in the atmosphere) on *Pioneer Venus* has in fact detected an aerosol haze that has been gradually dissipating; an analysis by Larry D. Travis of the Goddard Institute for Space Studies has shown that the concentration

In a step toward faster and more powerful integrated circuits, a Hughes Aircraft Company research team has made submicrometer transistors using focused ion beam lithography. The group made N-channel silicon MOSFETs with self-aligned submicrometer polysilicon gates. The smallest dimension of the gates ranged from 0.35 to 1.2 micrometers. The focused ion beam was used to expose a highly sensitive resist, which provided a mask for reactive ion etching the polysilicon by a combination of chlorine and fluorine-based etch gases. Outstanding electrical performance was obtained for the N-channel FETs, which employed a 100-angstrom-thick gate oxide.

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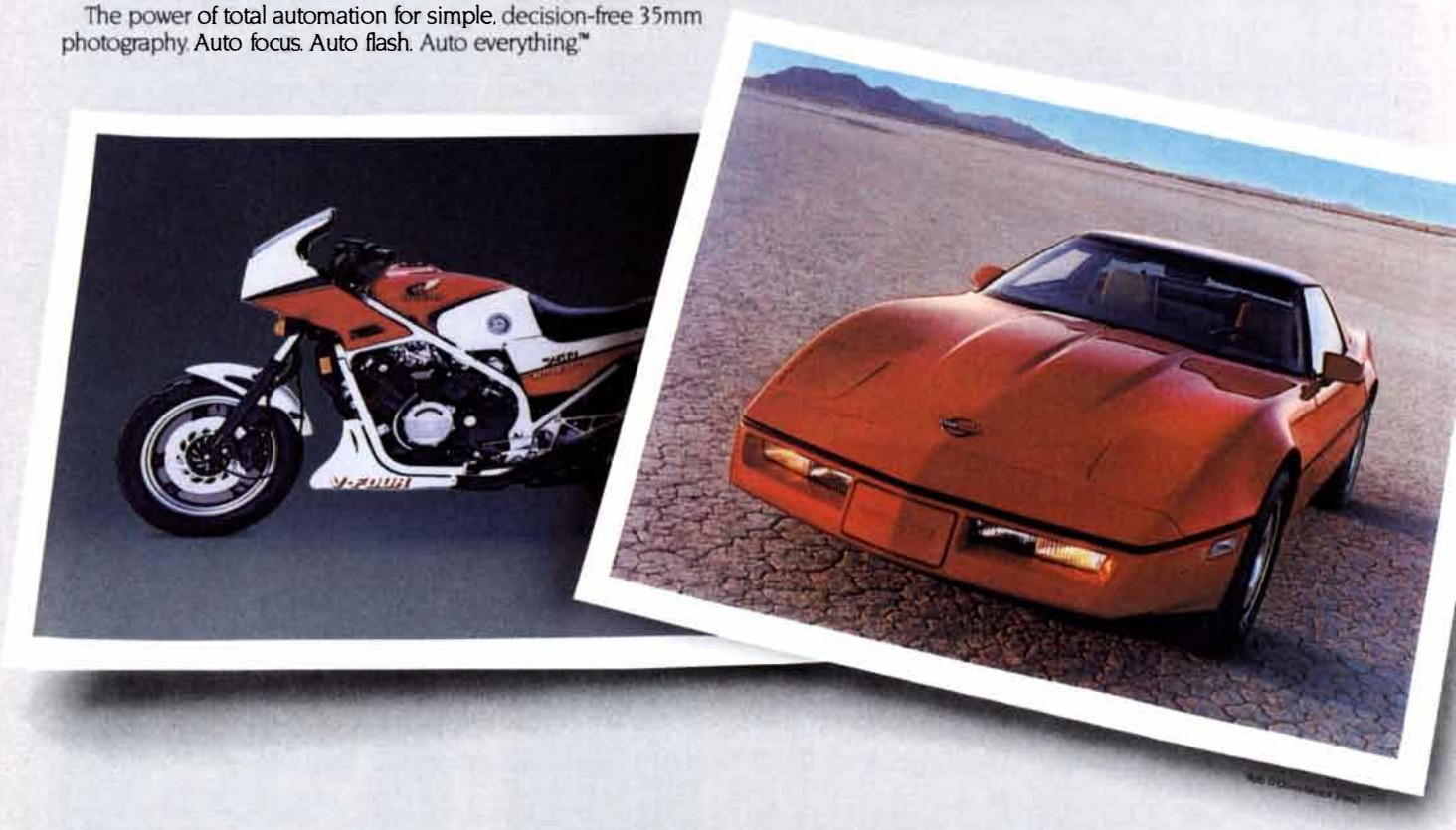

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of aerosols has also declined by 90 percent since measurements began.

Esposito has calculated that the putative 1978 eruption would have had to have been far more energetic even than Krakatau in order to have lifted the observed amounts of sulfur dioxide to an altitude of 70 kilometers. Smaller eruptions could conceivably occur more often on Venus without noticeably changing sulfur dioxide levels above the clouds. A curious hint to this effect comes from yet another instrument on *Pioneer Venus:* an antenna and amplifier that have been receiving intense low-frequency radio waves thought to have been emitted by strokes of lightning. Radio bursts associated with lightning are well known on the earth; they travel along the lines of force in the earth's magnetic field, and their motion is impeded by the ionosphere. Waves of somewhat higher frequency are slowed less and therefore arrive at a detector first, producing a characteristic "whistler" signal.

Frederick L. Scarf of TRW, Inc., and his colleagues have reported that *Pioneer Venus* detects radio bursts only when the local magnetic field is pointed from the orbiter down toward the surface, as would be expected with whistler waves. By tracing the magnetic field lines down to the surface, the investigators have been able to identify source regions for each burst. Writing in *Geophysical Research Letters,* Scarf and Christopher T. Russell of the University of California at Los Angeles report an interesting result: the lightning sources are clustered around Beta Regio, Phoebe Regio and Atla Regio. Scarf and Russell argue that the strong clustering would not be expected if the lightning originated in the cloud layer. They suggest that the lightning strokes result instead from electric-charge differentials in the plumes of erupting volcanoes, a phenomenon often observed on the earth.

If Venus does have active volcanoes, it must have a mantle that is in convective motion. On the earth convection in the mantle is strong enough to drive the motion of the continental and oceanic plates. On Venus, says Masursky, no evidence has yet been found of the hallmark of plate tectonics: a planet-girdling system of ridges where crust material rises out of the mantle and a system of trenches where it is subducted again. Venus may thus be intermediate in dynamism between the earth and the other bodies of the inner solar system (the moon, Mercury and Mars). Some investigators argue, however, that Venus may not yet have been observed with radar of resolution high enough to detect the evidence for plate tectonics. The planet is currently being mapped again by two Russian orbiters, and an American radar mapper with even higher resolution is scheduled to begin work in 1988. These missions should help to determine how dynamic the earth's sister really is.

Call of the Wild

Walter Litten, SCIENTIFIC AMERICAN's occasional correspondent on matters mycological, has lately been looking into the large-scale gathering of wild mushrooms.

"In much of the world wild mushrooms are picked for the market to supplement family income, but in English-speaking countries commerce in wild mushrooms has been very small until recently. Now it is growing rapidly. In 1982, it is estimated in the journal of the North American Mycological Association, a million pounds were commercially harvested in the Pacific Northwest. In 1983 the harvest there had tripled, believes Gary Lincoff of the New York Botanical Garden, the association's president. Much of the harvest of the highly prized chanterelles is shipped to European canneries and recrosses the Atlantic to American gourmet shops. Successful technology for the production in mushroom farms of the choice species—chanterelles, morels and king boletes—has proved elusive.

"The upsurge of mushroom hunting for pay has created tensions with local clubs of enthusiasts who hunt wild mushrooms for their own table and now find their favorite woods stripped. One of the two principal arguments against commercial harvesting is the danger that a poisonous species will find its way into a can. European countries with a tradition of market hunting for mushrooms practice various strategies for consumer protection against mushroom poisoning, such as requiring collectors to pass a mushroom-identification examination for licensing, limiting commerce to an official list of safe species and inspecting and certifying products for admittance to the marketplace.

"In North America enforcement mechanisms are sketchy to keep an occasional poisonous 'look-alike' out of elegant restaurants and the large Europe-bound casks filled from the baskets of relatively inexperienced casual collectors who are paid by the pound. Federal and state regulations cover in a general way the wholesomeness of produce and processed foods passing through the channels of commerce. Wild mushrooms present special problems in regulation. Species diversity in an area can vary widely from year to year. Close to good edibles or even intergrown with them often appear species of mushrooms difficult to identify even with microscope study, advanced literature and extensive experience with the particular taxonomic group. Information on the toxicity of the large number of widely

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but sporadically occurring mushroom species accumulates slowly.

"The other argument concerns fears that valuable fungi may face the same threat of extinction as redwood trees, ginseng plants and sea turtles. This argument is countered by pointing out that picking wild mushrooms is like picking apples from an apple tree, because a mushroom is merely an evanescent fruiting body put out by the long-lived hidden mycelium to distribute its spores into the air. The underground network of one-cell-wide mycelial threads remains to continue its mycorrhizal symbiosis with the forest trees.

"This defending argument may have been weakened by findings of Nils Fries of the University of Uppsala in Sweden. Spore-germination percentages in laboratory experiments are much higher for parasitic fungi and for fungi of the genera that feed on nonliving matter such as decomposing wood, grass or dung than they are for the mycorrhizal genera. In petri-dish culture Fries has found wide differences between species of mushroom-producing mycorrhizal fungi in their requirements for germination of even a small percentage of their spores. Chanterelles and the king bolete (*Boletus edulis*) are mycorrhizal, as are such favorites as matsutake (*Armillaria ponderosa*), slippery jack (*Suillus luteus*), the gypsy (*Rozites caperata*) and truffles. All of these are reported now to be commercially harvested in North American forests. In the case of the mycorrhizal *Leccinum,* a common and choice bolete genus of northern woods, Fries found that the only effective germination inducer is an actively growing mycelium of the same species. A mycelium of *Leccinum scabrum* failed to induce germination of *Leccinum aurantiacum* spores and vice versa. In another mycorrhizal genus, the largely poisonous *Hebeloma,* exudate from pine seedlings stimulated as much as .1 percent of spores to germinate.

"Since from a single mushroom may fall many millions of spores, a very small percentage of spore germlings must be encountering their specific requirements to grow beyond that stage into a tree-linked mycelium. Still other poorly understood conditions must be met for a mature mycelium to reveal its presence by producing mushrooms.

"Although results from laboratory experiments are not always transferable to natural conditions, it is possible that some fungi that are both mycorrhizal with forest trees and choice gourmet fare have spore-germination requirements most readily met in the immediate vicinity. This may suggest that distant dispersal of the species, although certainly not excluded, is a less likely function of the successful spore than renewal of the mycelium that lives under a mushroom allowed to finish sporulating in place."

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The Tornado

This intense whirlwind has been one of the most elusive phenomena in meteorology. New observation techniques are now revealing how it is spawned by a thunderstorm and promise to uncover the flow inside

by John T. Snow

Tornadoes have long been enigmatic, for the very reason that it is important to understand them. They strike sporadically and violently, generating the strongest of all surface winds and causing more deaths annually in the U.S. than any other weather phenomenon except lightning. This same behavior has made them inaccessible to planned observation. For example, it is now thought that the maximum wind speed possible in a tornado is on the order of 300 miles per hour, but this is only an estimate based on analysis of motion pictures and of damage to engineered structures. Estimates of atmospheric pressure changes, another crucial type of information, are available only for those few storms that happened to pass near weather stations. Meteorologists have thus had to build their sometimes elaborate models of tornado behavior on shaky observational foundations.

That is now changing. Since 1970 it has been possible to probe tornado-producing thunderstorms with Doppler radar and measure wind speeds within such storms from a safe distance. The result has been a vastly improved understanding of the updraft, the rising column of air at the heart of a thunderstorm, and of how it interacts with its environment. This has led to a much clearer picture of how a strong updraft begins to rotate and of how the spiraling winds intensify to the point where they give rise to a tornado.

Unraveling the dynamics of the tornado itself has proved to be a more elusive goal. The diameter of the funnel is rarely more than a few hundred meters, and the resolution of Doppler radar is not high enough to provide wind-speed measurements on that small a scale. Analysis of motion pictures has provided many clues concerning the airflow in the funnel, but theoretical descriptions of wind and pressure patterns in the core of a tornado still rely heavily on laboratory and computer simulations. On the horizon, however, are other measurement techniques such as lidar (operating on the same principle as radar but with light rather than microwaves), which promise to open the core to systematic observation and to remove some of the tornado's remaining mystery.

What Is a Tornado?

A tornado is the product of a thunderstorm, specifically of the interaction of a strong thunderstorm with winds in the troposphere (the active layer of the atmosphere that extends nine to 17 kilometers up from the ground). The process by which a tornado is formed is one in which a small fraction of the tremendous energy of the thunderstorm, whose towering cumulonimbus cloud can be 10 to 20 kilometers across and more than 17 kilometers high, is concentrated in an area usually no more than several hundred meters in diameter. Before going into the process in detail let me first describe the phenomenon itself.

A tornado is a vortex: air rotates around the tornado's axis about as fast as it moves toward and along the axis. Drawn by greatly reduced atmospheric pressure in the central core, air streams into the base of the vortex from all directions through a shallow layer a few tens of meters deep near the ground. In the base the air turns abruptly to spiral upward around the core and finally merges, at the hidden upper end of the tornado, with the airflow in the parent cloud. The pressure within the core may be as much as 10 percent less than that of the surrounding atmosphere: about the same difference as that between sea level and an altitude of one kilometer. Winds in a tornado are almost always cyclonic, which in the Northern Hemisphere means counterclockwise.

The vortex frequently—not always—becomes visible as a funnel cloud hanging part or all of the way to the ground from the generating storm. A funnel cloud forms only if the pressure drop in the core exceeds a critical value that depends on the temperature and the humidity of the inflowing air. As air flows into the area of lower pressure, it expands and cools; if it cools enough, the water vapor in it condenses and forms droplets. The warmer and drier the inflowing air is, the greater the pressure drop must be for condensation to occur and a cloud to form. Sometimes no condensation funnel forms, in which case the tornado reveals itself only through the dust and debris it carries aloft.

A funnel can be anywhere from tens of meters to several kilometers long, and where it meets the parent cloud its diameter ranges from a few meters to hundreds of meters. Usually it is cone-shaped, but short, broad, cylindrical pillars are formed by very strong tornadoes, and long, ropelike tubes that trail off horizontally are also common. Over a tornado's brief lifetime (never more than a few hours) the size and shape of the funnel may change markedly, reflecting changes in the intensity of the winds or in the properties of the inflowing air. Its color varies from a dirty white to gray to dark blue gray when it consists mostly of water droplets, but if the core fills with dust, the funnel may take on a more exotic hue, such as the red of western Oklahoma clay. Tornadoes can also be noisy, often roaring like a freight train or a jet engine. This may result from the interaction of the concentrated high winds with the ground.

Thunderstorms

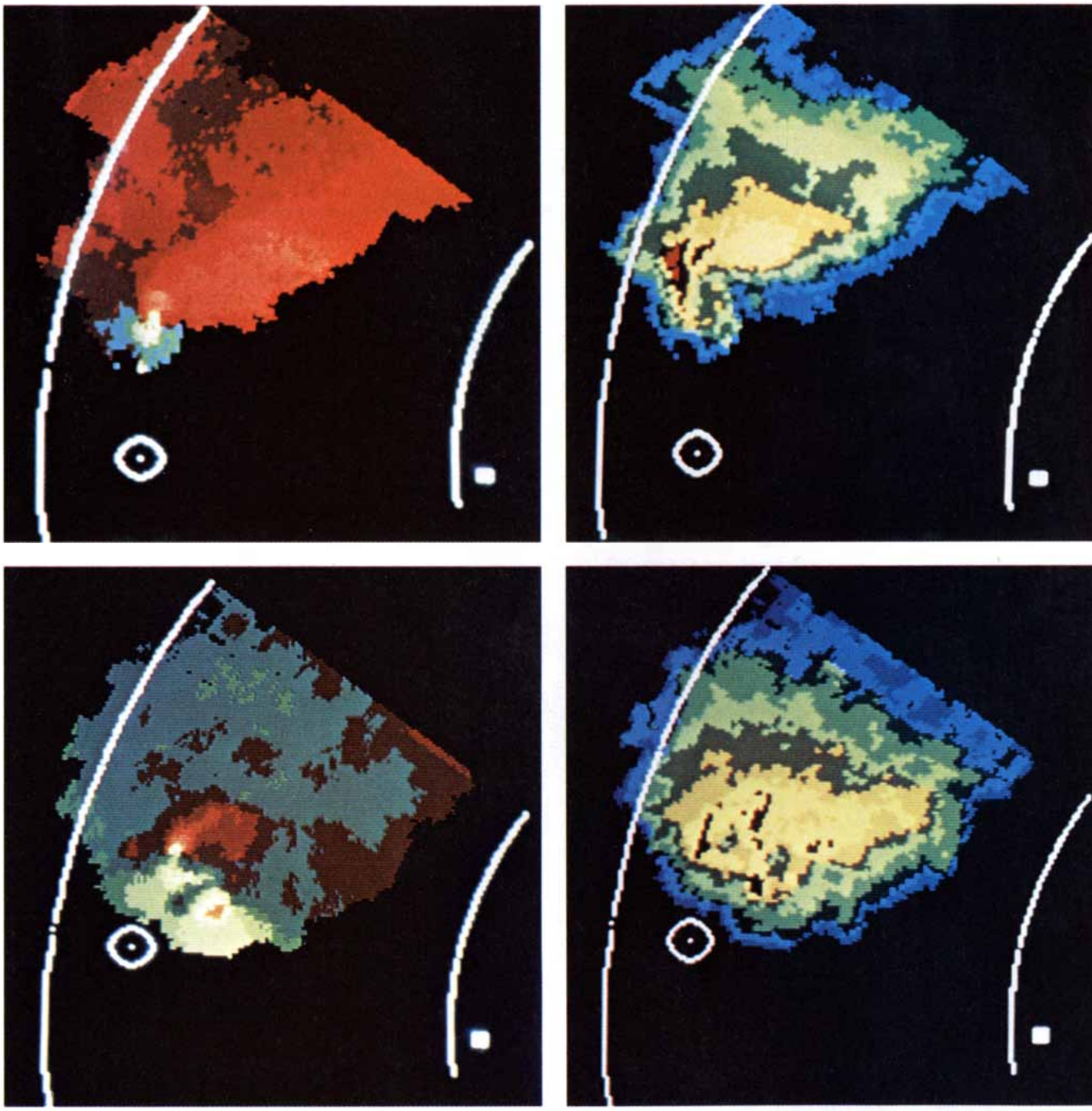
Tornadoes form in the updrafts of thunderstorms. Thunderstorms in turn occur in an unstable air mass: one in which a parcel of air, when it is lifted slightly, continues to accelerate upward.

In the atmosphere pressure always decreases with height, and temperature usually does. An air parcel that is forced upward cools as it expands in response to decreased pressure. In an unstable atmosphere, however, temperature decreases faster with height than the rate at which a rising parcel cools, and the parcel therefore can become warmer and hence less dense than its new environment. It then begins to rise freely. This upward motion, called free convection, is an energy-releasing process: the

potential energy stored in the unstable atmosphere is converted into the kinetic energy of motion.

In reality it is rare for the atmospheric temperature to drop faster than the rate at which dry air cools as it rises. Air near the ground, however, is normally humid. When this air is lifted, it cools to its dew point (at the "lifting condensation level," or LCL), and the water vapor in the air begins to condense. Condensation releases the latent heat that was added to the water when it evaporated. The result is a marked decrease in the rate of cooling in the rising parcel. Generally, if the parcel is forced just a short distance above the LCL, it will reach a level at which it becomes warmer than the surrounding air (the "level of free convection," or LFC). It will then rise freely until its temperature is once again in equilibrium with the environmental temperature. This equilibrium level defines the cloud top; the flat base of the thunderhead is at the LCL.

The typical unstable atmosphere consists of a warm, humid surface layer



SWIRLING WINDS OF A MESOCYCLONE, a rotating thunderstorm updraft that may give rise to a tornado, show up clearly on Doppler radar (*left*) but not on conventional radar (*right*). The images are horizontal cross sections, at altitudes of 600 meters (*top*) and 7,600 (*bottom*), of a tornadic storm that struck Binger, Okla., on May 22, 1981. Conventional radar measures the intensity of precipitation from the strength of the storm echo; areas of least intensity are blue, those of greatest intensity are red. The presence of the mesocyclone is suggested only by the hook shape of the echo in the top image, the result of rain being entrained by the rotating winds. Doppler radar measures wind speed and direction from the frequency shift between the echo and the transmitted beam; red indicates winds moving away from the radar, green indicates winds toward the radar and blue indicates winds perpendicular to the beam. Light colors designate strong winds. The mesocyclone leaves a clear "signature": adjacent red and green areas, indicating a 180-degree wind shift over a short distance. The signature was visible to an altitude of 12 kilometers in the Binger storm, which generated an unusually violent tornado. These images were made by the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory in Norman, Okla.

overlain by cool, drier air. Often the two layers are separated by a "capping inversion": a thin layer in which the temperature increases with height. A parcel of air rising into the inversion layer will be cooler than the air around it and will tend to be pushed back down. An inversion is thus very stable: it suppresses upward motion and bottles up instability. As a day progresses and the ground is heated by the sun, the air under such a capping inversion warms further and may also become more humid because of evaporation. If the inversion is locally eroded by mixing from below, or if large-scale effects lift the entire inversion layer, the now highly unstable surface layer erupts explosively at a few points. Surface air flows horizontally into these points of eruption, forming tall thunderstorm clouds.

One process that can weaken or completely dissipate a local inversion is the passage overhead of a maximum in the jet stream, the river of strong winds flowing from west to east at an altitude of eight to 12 kilometers. The jet stream over the U.S. is usually associated with the polar front, the boundary between polar and tropical air masses, and it moves north and south with the front on a seasonal basis. The core of the jet is roughly 100 kilometers wide (in the north-south direction) and one kilometer deep. Wind speeds in the jet range from 50 m.p.h. to an estimated high of 200 m.p.h. (Whereas atmospheric scientists normally refer to wind speeds in meters per second, here I shall use miles per hour because it is more familiar to the general reader.) Within the jet "packets" of particularly intense winds, several hundred kilometers long, move downstream, pushing air down in front and drawing air up behind them. The regional uplifting that occurs to the rear of a wind maximum may dissipate an inversion, promoting the formation of thunderstorms, or it may intensify storms that are already developing. When a thunderstorm engenders a tornado, this type of "favorable upper-air support" is almost always present.

Even with such support, however, an updraft will develop only if the unstable surface air is nudged up to the level of free convection. The required mechanical lifting can take many forms; a good example is air being driven up a slope by a large weather system. Another type of lifting takes place at a cold front, where cold, dense air is advancing into a warmer region, cutting under the warmer air and squeezing it upward.

Why in the Middle West?

Tornadoes have occurred in every state of the U.S. and are also known in other parts of the world. Australia appears to rank second behind the U.S. in the frequency with which it is struck by tornadoes, although accurate comparisons between countries are difficult to make because statistics for sparsely settled areas of the world (such as Australia) may not be reliable. The world's tornado hot spot, however, is unquestionably the central and southeastern U.S., with the area of maximum frequency in northern Texas, Oklahoma, Kansas and parts of Nebraska and Missouri. In the spring and to a lesser extent in the fall everything needed for the formation of severe, tornado-generating thunderstorms is present in this region: a highly unstable distribution of temperature and humidity in the atmosphere, strong cold fronts that provide the lift needed to start convection, and winds in the upper atmosphere favorable for the formation of strong updrafts.

These conditions are most likely to arise simultaneously along the polar front, the boundary between the continental polar (cP) air mass and warmer, more humid maritime tropical (mT) air. The cP air cools in long winter nights over western and central Canada, and its southward spread is channeled to the southeast and east by the Rocky Mountains. The northward movement of mT air from the Gulf of Mexico is enhanced by the clockwise flow around a high-pressure cell centered east of Bermuda.

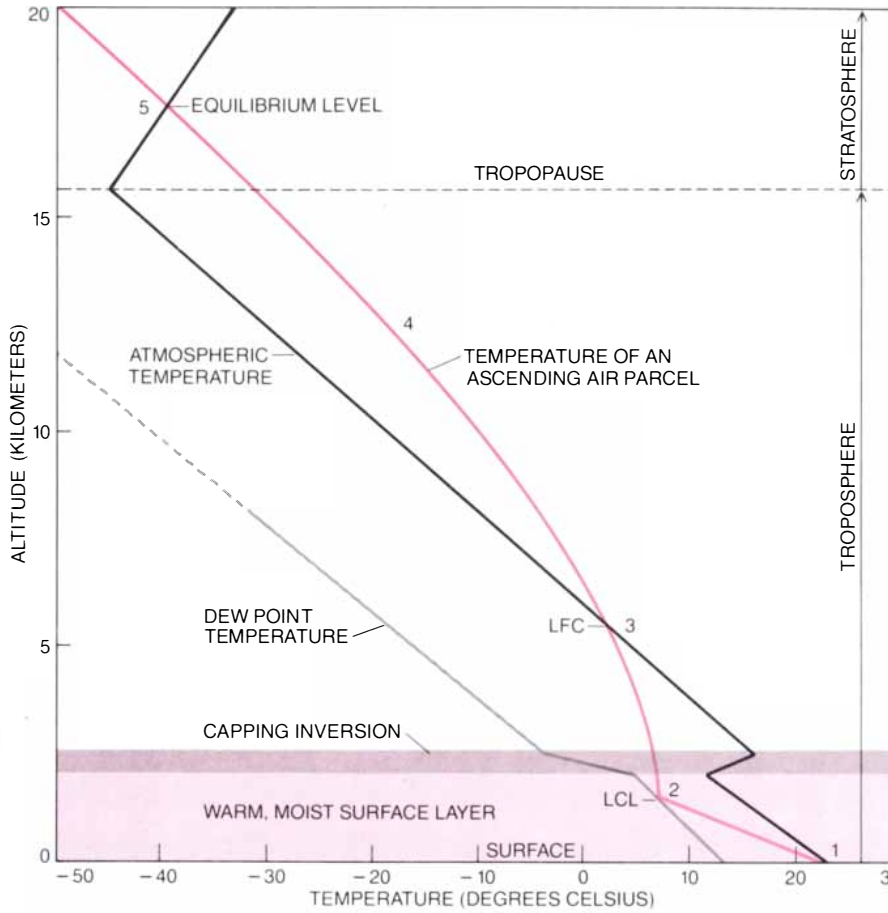
SOUTHEASTERN KANSAS TORNADO struck soon after 7:00 P.M. on June 30, 1974. It is shown early in its development, when it was still quite weak and its funnel cloud was long and narrow; as the funnel gained intensity it widened. This was the second of two tornadoes spawned by the same thunderstorm, each lasting about 20 minutes. Photograph was made from 11 miles away by David Hoadley.

As a result the two air masses collide most forcefully in the central U.S., and in this region the south-to-north temperature contrast at ground level is very sharp, particularly in the spring. Since atmospheric pressure decreases faster with height in cold air than it does in warm, the temperature contrast is normally accompanied by a pressure gradient aloft that produces a strong jet stream blowing parallel to the polar front. The intensified winds in the upper atmosphere create regional conditions that favor upward motion and storm formation.

If the polar front is disturbed slightly, say by a small change in the path of the jet stream, warm, moist air will begin to bulge northward to the east of the disturbance center, while to the west of the disturbance center cold air will start to flow southward. The resulting winds give rise to a cyclonic (counterclockwise) flow around a low-pressure center at the crest of the wave-shaped disturbance. Such "wave cyclones," which extend 1,000 to 2,000 kilometers in a west-to-east direction, move eastward along the front, and the southerly winds in their southeastern quadrants help to draw the mT air toward the north. As the warm, humid mT air moves into the central U.S. in the lower half of the troposphere, it flows under colder, much drier air. The resulting atmospheric temperature structure is very unstable. At the trailing edge of the wave cyclone a rapidly advancing cold front cuts under the warm mT air, providing the lift needed to initiate convection. It is along this cold front that strong thunderstorms often form.

The favored region for the production of strong thunderstorms in the central U.S. moves in a seasonal cycle, beginning near the Gulf Coast in late February, when the cP air mass has reached the limit of its expansion to the south. The storm track gradually moves northward across the plains as spring progresses, the land warms up and Gulf air drives back the polar air mass. By early summer storms are striking the Dakotas. From late summer to early fall is a relatively quiet time because the temperature contrast across the polar front is weak. In the late fall the contrast intensifies again and the storm-production region retreats south toward the Gulf, completing the cycle. The retreat is somewhat faster than the northward advance, and so the period of conditions favorable to storm production is shorter in the fall than it is in the spring.

On the whole the monthly distribution of tornadoes follows the same pattern. About 74 percent of all tornadoes in the U.S. are reported from March to July, with the peak months being April (15 percent), May (22 percent) and June (20 percent). April tornadoes kill the most people; the contrast between the two air masses is strongest from late March through April, with the result that many severe thunderstorms and the majority of violent tornadoes come in that period. There is a weak secondary maximum in tornado frequency in October and November, reflecting the production of tornadoes by thunderstorms accompanying hurricanes as well as by thunderstorms along the polar front.

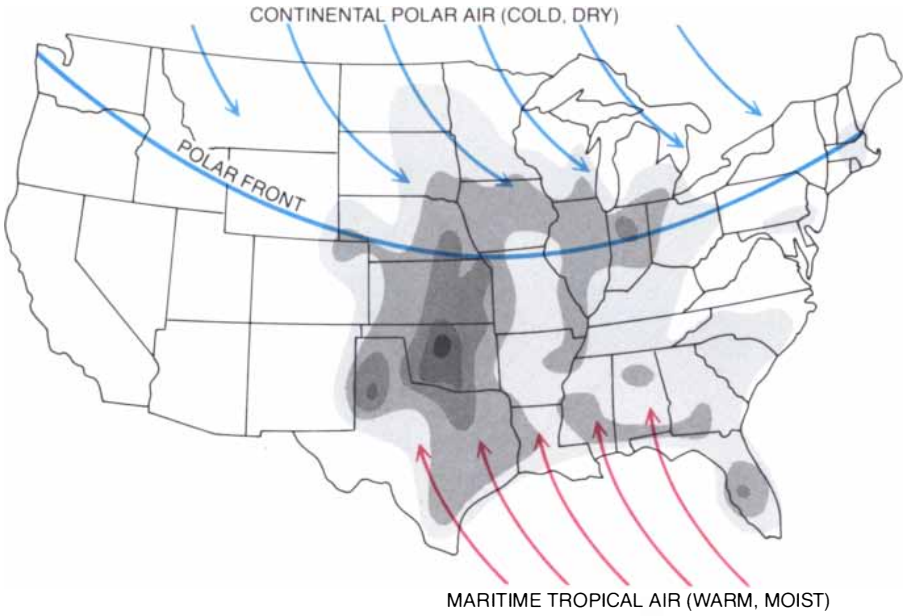


THUNDERSTORM UPDRAFTS form when the temperature of the atmosphere decreases rapidly with height. A parcel of warm, moist air forced upward from the surface (*1*) will initially cool faster than the surrounding atmosphere. Its rate of cooling slows markedly after its temperature reaches the dew point at the "lifting condensation level," or LCL (*2*), because condensation of water vapor begins to release latent heat. If the parcel is forced above the LCL, it may eventually reach the "level of free convection," or LFC (*3*), above which it is warmer than its environment. It will then rise freely (*4*) until it is once again in equilibrium with its surroundings (*5*). In a strong storm the updraft overshoots the equilibrium level at the top of the cloud.

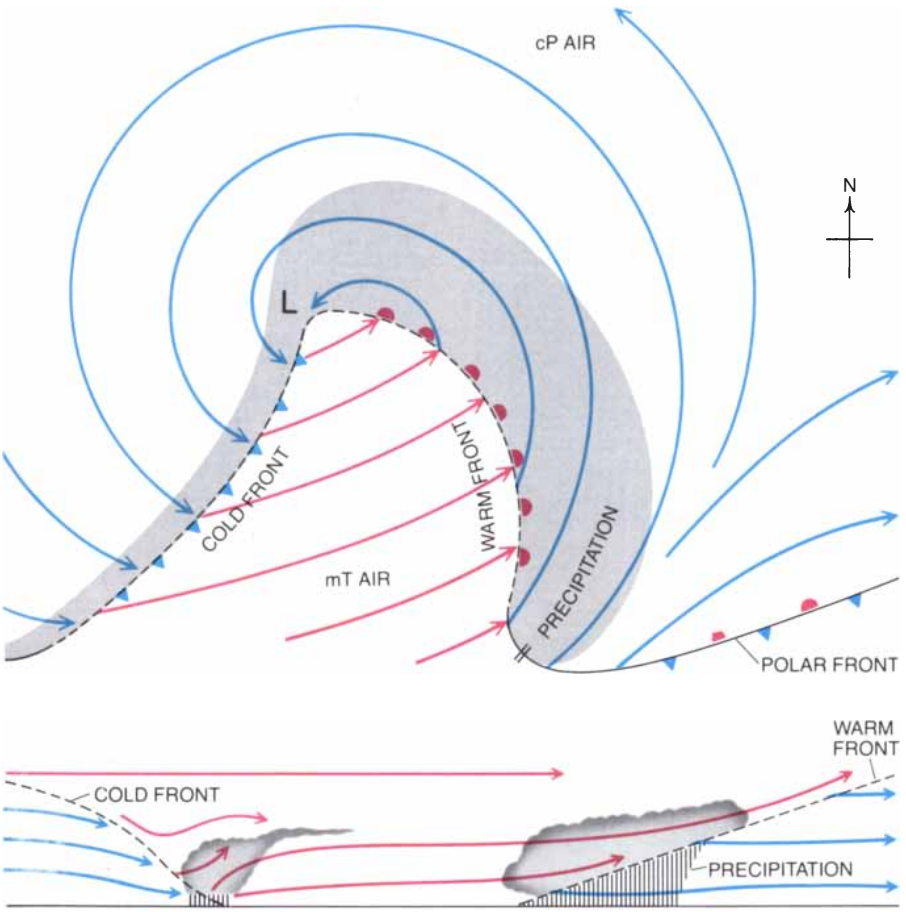
Tornado Formation

A strong thunderstorm provides the concentrated, persistent updraft needed to launch a tornado and to prevent its low-pressure core from filling from above. When the top of such a storm is viewed from a satellite, it usually displays a characteristic sequence of rising "bubbles" of cloud material that overshoot the mean cloud top by two to four kilometers and then subside back into the cloud mass. The bubbles are an indicator of a strong updraft with a high degree of organization in the storm. For a tornado to be formed, however, the air in the updraft must begin to rotate as well. That can happen if the updraft concentrates the spin contained in the horizontal winds in the troposphere.

Not just any winds will do. It appears that they must be strongly sheared vertically in both magnitude and direction: the wind speed must increase with height, and the direction must veer from southeast to west. Vertical shear in wind speed provides a source of rotation about a horizontal axis. To understand why, imagine a paddle wheel placed in the wind field, with the wind coming from the left. Since the wind hitting the top of the paddle wheel is stronger than that hitting the bottom, the wheel will begin to spin in a clockwise direction. Similarly, a parcel of air in the sheared wind field will have a rotational component of motion, because the top of the parcel is moving faster than the bottom. When the winds begin to interact with a strong updraft, this rotation about a horizontal axis can be "tilted," becoming rotation about a vertical axis. Shear in wind direction—as opposed to speed—is a more direct source of vertical spin; winds veering from southeast to west



FREQUENCY OF TORNADOES is greatest in the central U.S., where continental polar air masses channeled to the southeast by the Rocky Mountains collide with maritime tropical air flowing north out of the Gulf of Mexico. In the spring the temperature contrast across this polar front is sharpest, creating unstable atmospheric conditions that favor the formation of severe thunderstorms. The darkest shading designates regions of greatest tornado frequency.



WAVE CYCLONE, an eastward-moving disturbance in the polar front that promotes the formation of tornadic thunderstorms, is shown in top and side views. Maritime tropical air flows northeastward and cold air flows to the south, creating a counterclockwise circulation around a low-pressure center at the wave crest. The wave is from 1,000 to 2,000 kilometers wide in the east-west direction. Its leading edge is a warm front, where warm air rises gradually over cold, forming sheetlike stratus clouds. The trailing edge, a cold front, is steeper and moves faster than the warm front. It sharply lifts the warm air, which begins to rise freely, forming thunderstorms.

promote a cyclonic (counterclockwise) flow in the air converging under the storm updraft.

According to current models, a severe thunderstorm gives rise to a tornado in two steps. First the entire thunderstorm updraft begins to rotate; the spinning column of rising air, 10 to 20 kilometers in diameter, is called a mesocyclone. (If it goes on to generate a tornado, which the majority of mesocyclones do not, it is called a tornado cyclone.) Doppler radar observations have shown that the rotation begins in the mid-troposphere, at altitudes of four to eight kilometers. Tilting appears to be the principal mechanism operating at this stage.

Once rotation has begun at mid-levels it builds down toward the ground through a "dynamic pipe" effect. Along the rotating column the pressure field is now in balance with the strongly curved wind field: the inwardly directed force acting on air parcels as a result of the reduced pressure at the center of the column is countered by the outwardly directed centrifugal force resulting from the parcels' rotation about the center. In such a condition, called cyclostrophic balance, air can easily move around and along the axis of the cyclone, but radial motions (toward or away from the axis) are strongly suppressed. Whereas before some air entered the updraft column at mid-levels, now almost all the air flowing along the cyclone's axis is sucked up through its lower end. The cyclone acts as a dynamic pipe; it is rather like the hose of a vacuum cleaner, except that instead of being channeled by the wall of the hose the airflow in the cyclone is constrained by its own swirling motion.

The result is an intensification of the updraft and hence of the converging winds under the cyclone. Because of the shear in wind direction, the air converging into the updraft has a component of spin about the center of the column. A fundamental law of physics requires that an air parcel's angular momentum about its vertical axis, which is proportional to its momentum (mass times velocity) and to its distance from the axis, be conserved. As the air parcel's distance from the center decreases, its velocity must therefore increase; it begins to spin faster about the center, just as a figure skater spins faster when she pulls her arms into her body. Thus the dynamic pipe intensifies the rotation at its lower end, which in turn extends the pipe downward as the centrifugal force gets strong enough for cyclostrophic balance to be established.

As air parcels converge into the base of the pipe they turn and accelerate upward. In doing so they are "stretched" vertically. Stretching narrows the diameter of the mesocyclone to about two to six kilometers, further increasing the speed of its winds as the angular momentum of the air, now rotating over a

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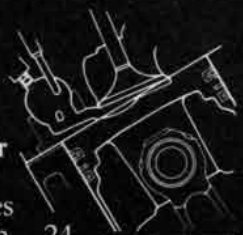

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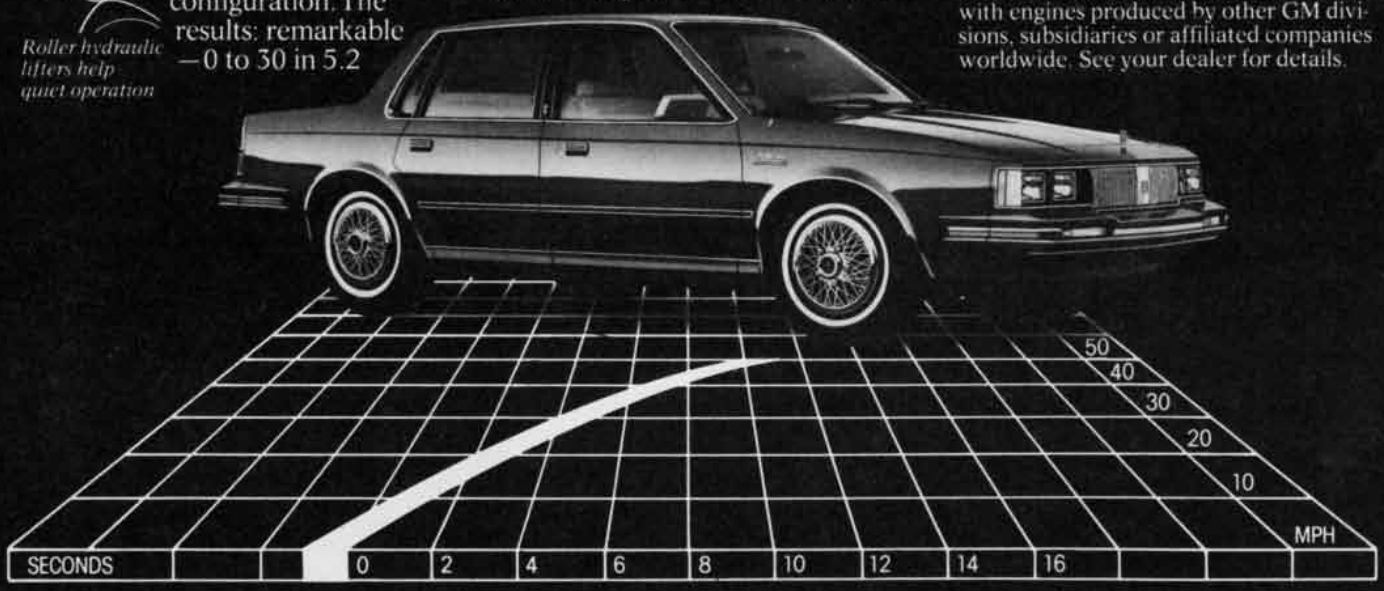

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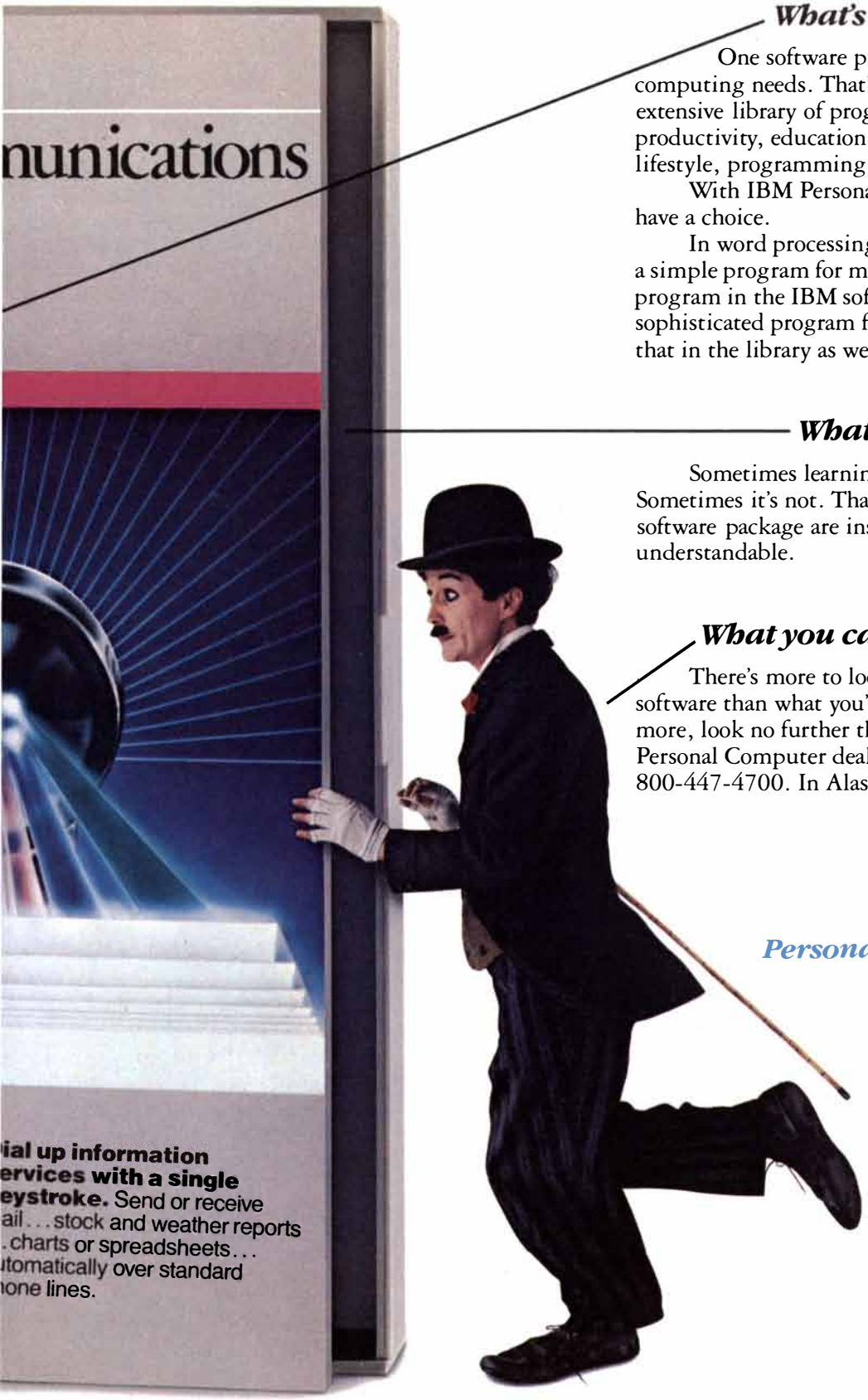

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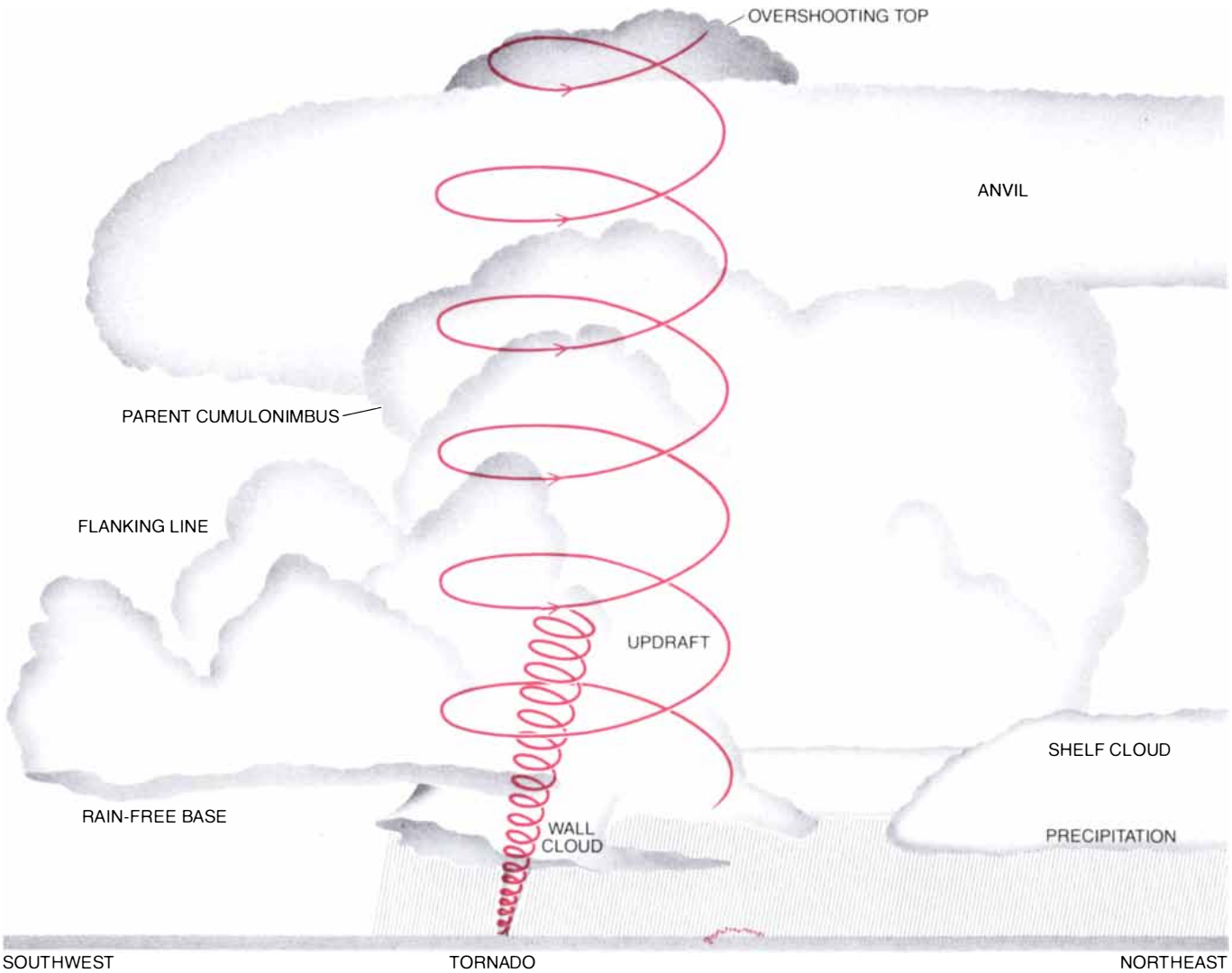
smaller distance, is conserved. Tilting, the dynamic-pipe effect, convergence and vertical stretching, processes that feed on one another, can eventually form a mesocyclone that extends from about one kilometer above the ground to near the top of the thunderstorm at about 15 kilometers. Surface winds with speeds as high as 75 m.p.h. can blow over the large region under the swirling column. The rotation in the mesocyclone is still too diffuse and too far aloft, however, to generate truly intense surface winds.

The generation of such winds comes in the second step by which a severe thunderstorm gives rise to a tornado: the formation of the actual tornado core. For reasons that are not yet understood, a region of enhanced convergence and stretching, no more than one kilometer in diameter, appears to develop inside the mesocyclone, toward one side. Doppler radar observations again suggest that the intensification of spin begins aloft, at altitudes of several kilometers, and then quickly builds down toward the ground. Over such a small area the rotational motion is strong enough for the dynamic pipe to reach to within several tens of meters of the ground. Close to the ground friction prevents the establishment of cyclostrophic balance by slowing the rotational motion.

In response to the pressure gradient between the tornado core and the surrounding atmosphere, air streams inward through a thin layer near the ground. Owing to inertia the inflow actually overshoots its equilibrium radius, conserving its angular momentum and picking up speed as it approaches the center of the core before turning sharply to spiral upward. As a result the highest wind speeds are found in a small ring-shaped region at the base of the vortex. Because friction with the ground ultimately limits the rate of airflow into the base, it prevents the tornado from filling from below.

Evolution and Structure

A typical tornado-producing thunderstorm has a lifetime of two to three hours and usually engenders only one relatively short-lived tornado. Most of the storm's lifetime consists of initial organizational and final dissipative phases. The period of maturity during which a tornado is most likely to form may last for only a few tens of minutes. In this phase the storm moves across the land, sweeping up a continuous supply of humid, unstable air. On rare occasions the updraft and the attendant tornado cyclone can approach a quasi-steady state, in which case the storm is called a super-



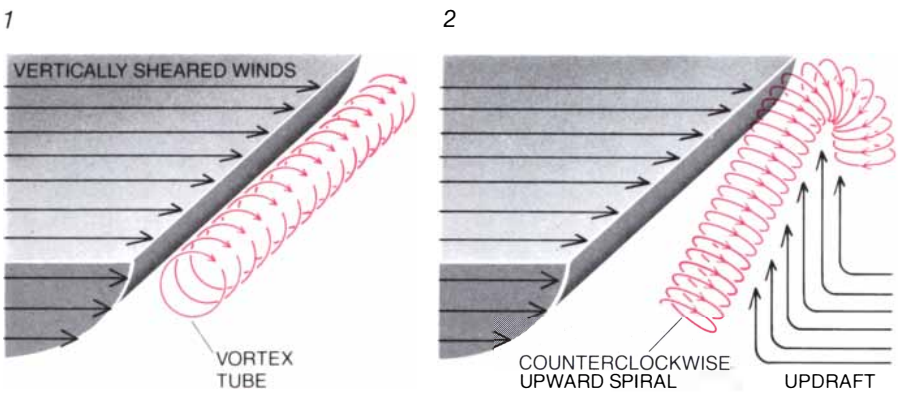
ANATOMY OF A TORNADIC THUNDERSTORM reveals its major features. It is moving to the northeast, and its main inflow is along the southern flank; warm, unstable air rises over cool air flowing out of the storm to form the flanking line, which merges with the parent cumulonimbus cloud. The rain-free base of the flanking line is at the lifting condensation level, and the flat top of the cloud is at the equilibrium level. Because the updraft is strong, rising air overshoots the equilibrium before falling back into the "anvil." The lower end of the rotating mesocyclone is the wall cloud. The shelf cloud marks the location of the gust front, where a cool downdraft caused by precipitation undercuts warm air ahead of the storm. The illustration is based on sketches by Charles A. Doswell III and Alan Moller.

cell. In some supercells the strength of the tornado cyclone pulsates, creating a sequence of tornadoes. Tornado "families" have been observed with up to eight members spread over a distance of 200 to 300 kilometers. On rarer occasions a tornado cyclone will remain active for several hours, forming a single, long-lasting tornado with a continuous damage path. The most damaging tornado ever recorded was the Tri-State Tornado of March 18, 1925, which caused 689 deaths along a 352-kilometer path extending from southeastern Missouri through Illinois to southwestern Indiana.

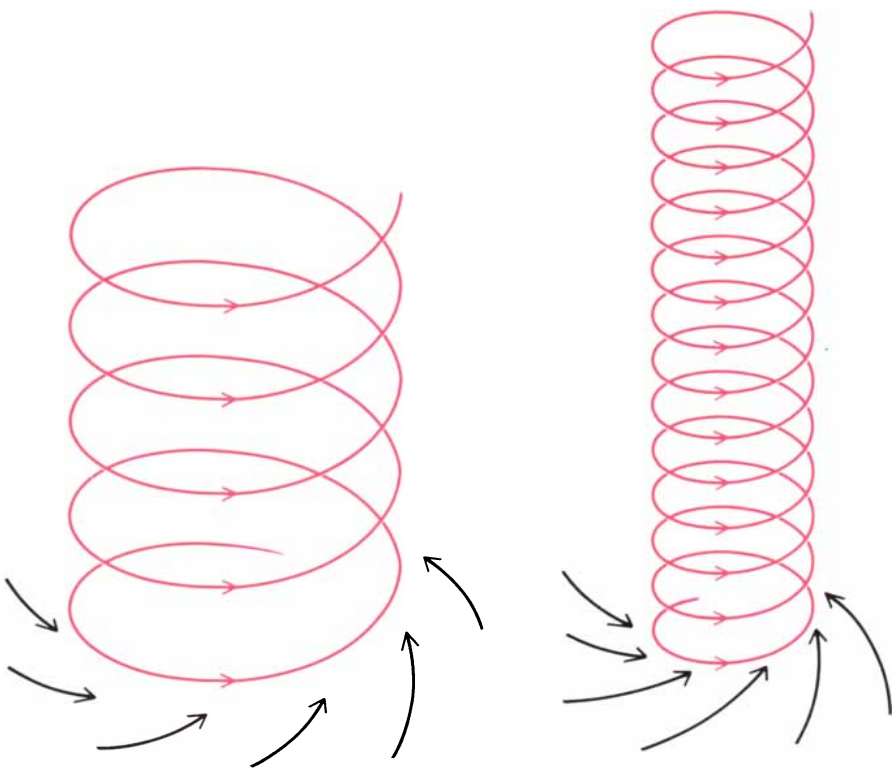
Tornado vortexes vary a great deal in shape and size. Drawing conclusion about the dynamics of the vortex core from funnel observations is tricky because not only the core structure but also the moisture content of the air, the properties of the ground and other factors affect the appearance of the funnel and may even change in the tornado's lifetime. Nevertheless, a few generalizations can be made.

Tornadoes that are classified as "weak" according to the scale developed by T. Theodore Fujita of the University of Chicago (those with maximum wind speeds of between 40 and 112 m.p.h.) typically have a single, nonturbulent funnel, often in the form of a long, narrow, inverted cone with a smooth surface. The funnel often does not reach all the way to the ground, and vertical wind velocities appear to be greatest along the central axis. In contrast, the vortex of a tornado classified as "strong" (wind speeds from 113 to 206 m.p.h.) is generally turbulent, and its funnel cloud, a broad column that almost always extends to the ground, has a rolling, boiling appearance. Vertical wind velocities in strong tornadoes tend to be highest in a ring around the central axis; at the axis itself they are reduced and may even be reversed, creating a downdraft. Between the typical weak and strong vortexes, of course, there are intermediate forms.

Many tornadoes classified as "violent" (winds exceeding 207 m.p.h.) look quite different: the central core appears to be a calm, clear "eye" surrounded by two or more subsidiary vortexes. The nonswirling, descending air in the eye is drawn down from aloft by the extremely low pressure at the ground; the eye is clear because water droplets in the air evaporate as the air descends and is warmed. At the ground this inner flow turns outward and meets the primary inflow coming from outside the vortex core. The combined flow turns upward, forming subsidiary vortexes in a cylindrical ring surrounding the central downdraft. The subsidiary vortexes spin rapidly about their own helical axis and at the same time rotate about the center line of the tornado. It appears that the fastest surface winds known to man, approaching 300 m.p.h., blow at the bases of the subsidiary vortexes. The recognition of this interlocking multiple-vortex structure in the early 1970's was a major discovery, because it explained the complex cycloidal swaths of damage left by the most powerful tornadoes.



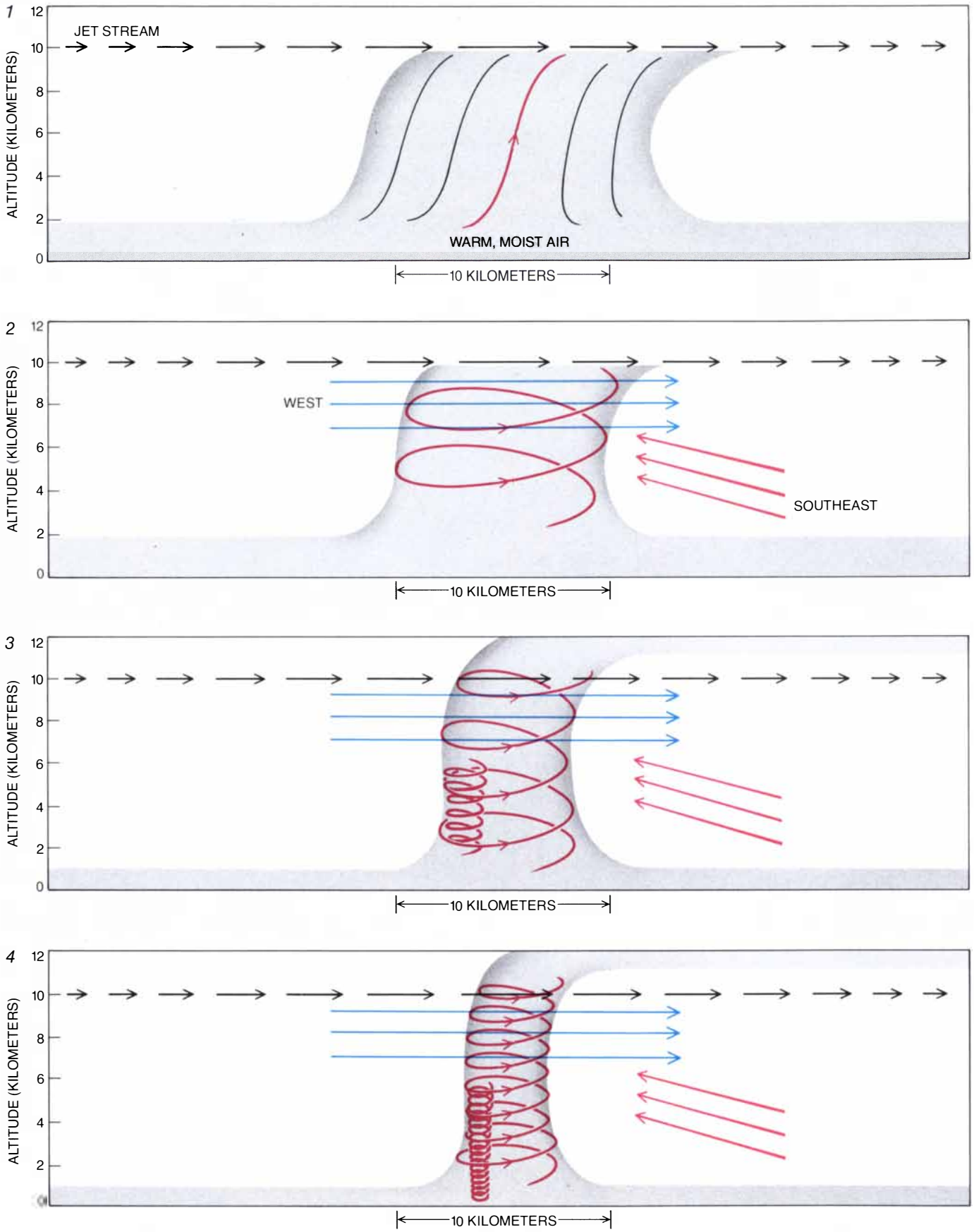
TILTING of horizontal spin into vertical spin starts the rotation of a thunderstorm updraft, according to current theory. Spin about a horizontal axis, illustrated by the vortex tube, is always present when wind speeds increase with height (*1*), because the top of a given air parcel moves faster than the bottom. When the vertically sheared winds are deflected by a strong updraft (*2*), the axis of spin is tilted toward the vertical. The resulting upflow has a counterclockwise spin; the clockwise-spinning far side of the tube is generally in the storm's precipitation downdraft.



CONVERGENCE AND STRETCHING intensify the counterclockwise rotation initiated by tilting and extend it upward. The rotating updraft column in the mid-troposphere accelerates the winds converging at its lower end, because the centrifugal force suppresses flow into the sides of the column (the "dynamic pipe" effect). Shear in the direction of the converging winds gives the inflow spin about the vertical axis, and so rotation builds downward toward the ground. At the same time the enhanced convergence compresses the column and stretches it upward. Because the column is narrower, it must spin faster to conserve its angular momentum.

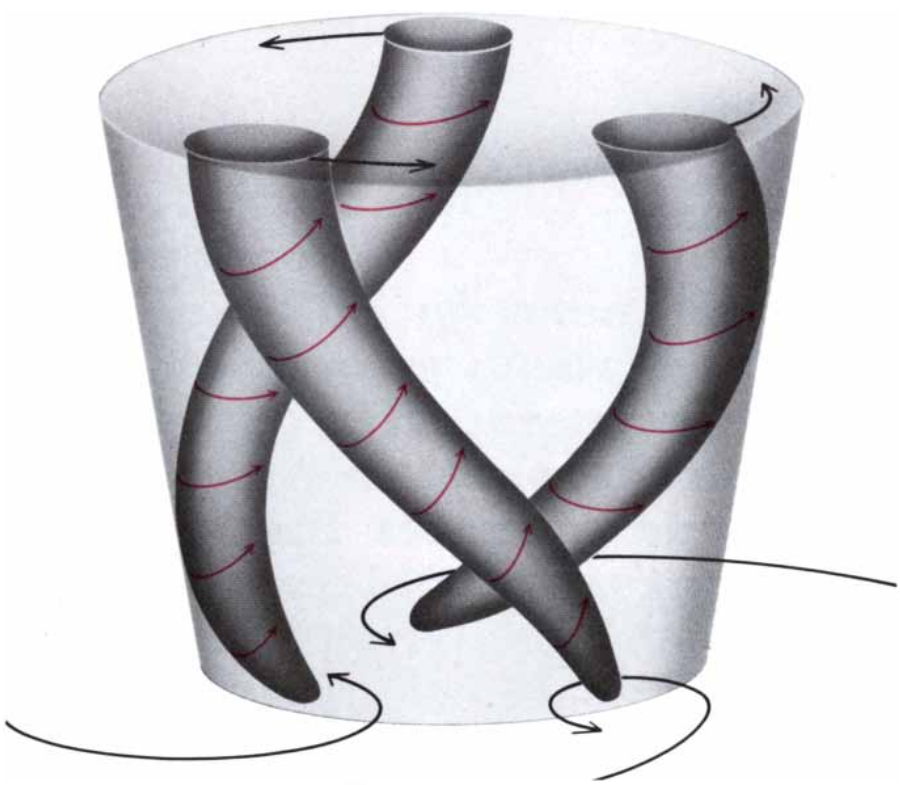
Unanswered Questions

In spite of such recent advances, understanding of tornadoes remains in some ways quite limited. For example, the picture I have presented of the chain of events leading to the formation of a tornado is incomplete in that it applies chiefly to strong tornadoes. Weaker twisters may develop not in the main storm updraft but along the leading edge (the "gust front"), where rain-cooled air flowing out of the parent thunderstorm undercuts and lifts warm



STAGES OF TORNADO FORMATION are shown. Atmospheric instability generates a strong updraft that is further intensified by a passing maximum in the jet stream (*1*). The updraft, interacting with winds that are vertically sheared in both speed and direction (*2*), begins to rotate in the mid-troposphere, forming a mesocyclone. The mesocyclone narrows and intensifies as it builds down toward the ground and is stretched upward (*3*). Meanwhile a small area of enhanced convergence, the nascent tornado, forms inside the cyclone. As the cyclone intensifies further, the same processes that generated it (tilting, the dynamic-pipe effect, convergence and stretching) form the tornado core (*4*). Rotation in the core, unlike that in the cyclone, is strong enough to allow the tornado to extend all the way to the ground. As the evolving vortex approaches the ground level there is a rapid drop in surface pressure and an increase in surface wind speed.

MULTIPLE-VORTEX STRUCTURE is characteristic of violent tornadoes. This one killed one person when it struck Friendship, Okla., on May 11, 1982. Although only three subsidiary vortexes are visible in the photograph, at least four were observed. "Storm chasers" tracked the tornado for two hours, during which time it switched back and forth from a multiple-vortex to a single-vortex structure. The parent tornado, visible as a bowl-shaped cloud surrounding the subsidiary vortexes, was roughly three-quarters of a mile in diameter. The photograph was made by Howard B. Bluestein of the University of Oklahoma from about one and a half miles away.



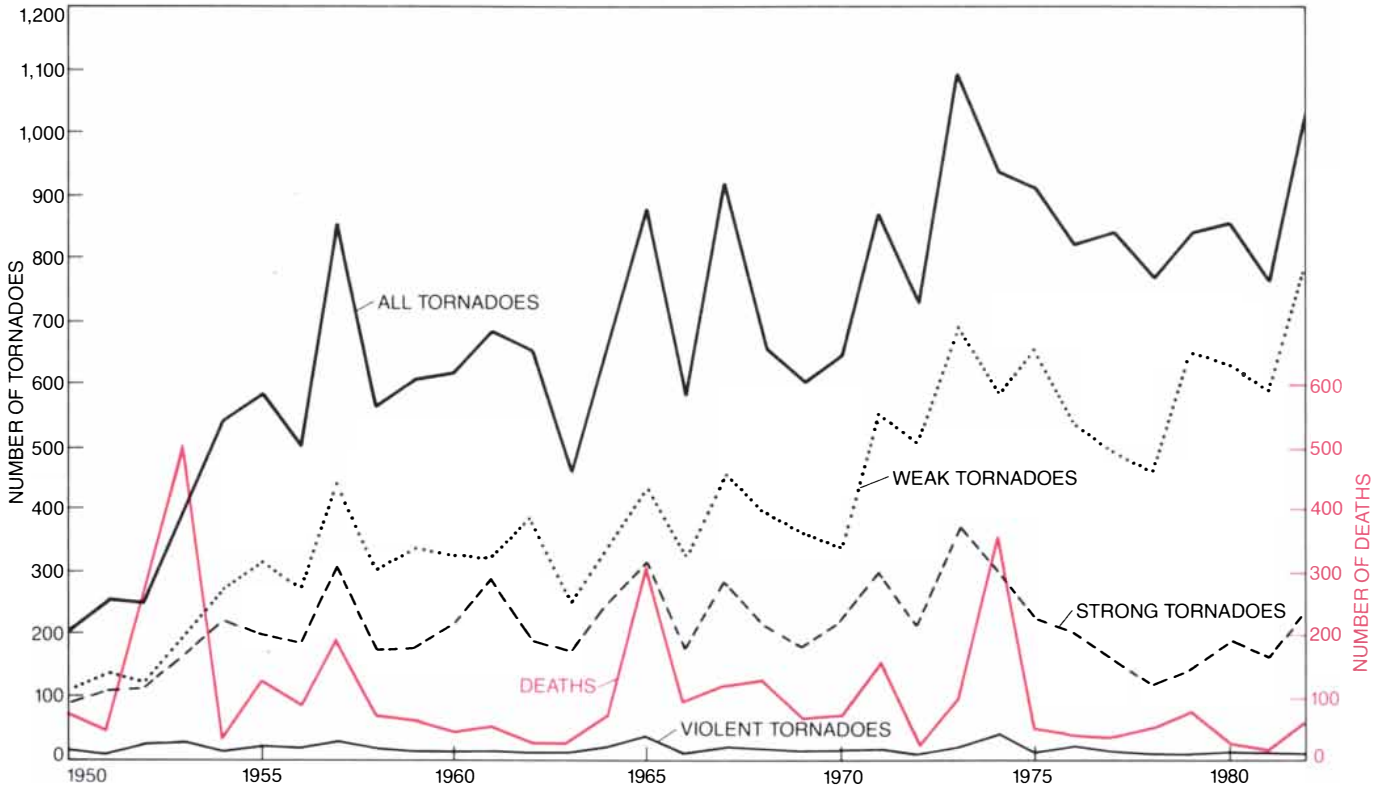
SUBSIDIARY VORTEXES in a multiple-vortex tornado rotate about their own axis as well as about the central axis of the parent tornado. In a violent tornado an extreme pressure drop in the core near the ground can cause a downdraft along the central axis. The subsidiary vortexes form at the edge of the parent vortex, where the downdraft meets air flowing into the core. The strongest winds and pressure drops are seen at the base of the subsidiary vortexes.

inward-flowing air. There also seem to be several other processes that can yield the concentration of spin needed to generate a tornado, and the details of these mechanisms and the relations among them remain puzzling.

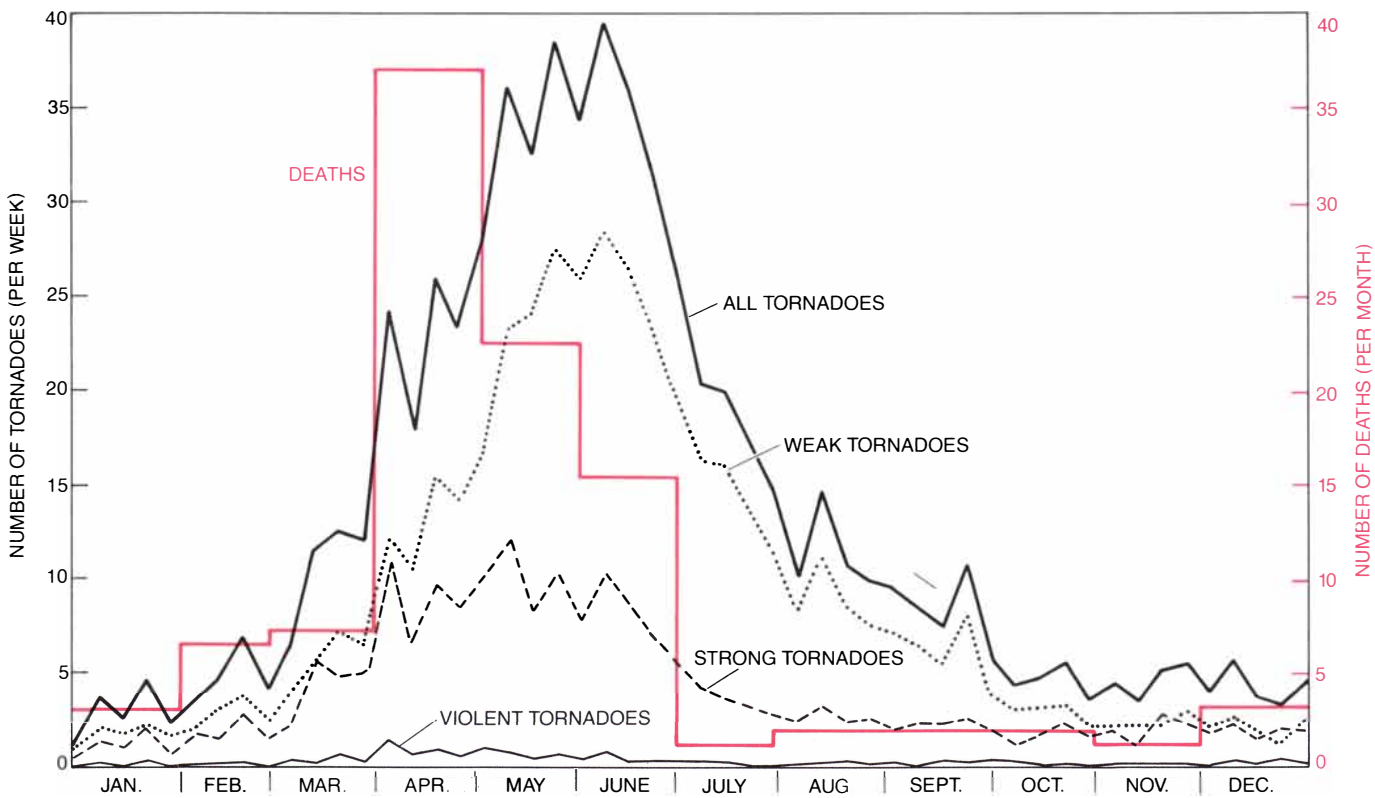
Similar fundamental gaps abound in knowledge of the tornado core. There are almost no quantitative data on wind speeds and pressure drops in this region. Such information is of more than academic interest: architects and engineers in areas subject to tornadoes, for instance, would like to know just how wind-resistant they need to make their buildings, without either overbuilding or taking dangerous risks. Research meteorologists, on the other hand, need such information to answer basic questions: how spin is enhanced in a mesocyclone to create a tornado, how the updraft in the core is structured and how it interacts with horizontal winds, and how and at what altitude the core merges with the flow in the tornado cyclone.

The violent nature of tornadoes has prompted meteorologists to study more approachable types of columnar vortexes, with some success. In 1971 Fujita's aerial observation of a large multiple-vortex dust devil (a relatively weak whirlwind) yielded the first confirmation of the idea that multiple vortexes might exist in violent tornadoes as well. Since 1970 a long series of experiments has focused on waterspouts (a type of vortex occurring over the ocean), which tend to have lower wind speeds than their land-based cousins and which are common in early summer around Key West, Fla. Investigators have photographed waterspouts and have flown aircraft to drag instrument packages through their core. It is not clear, however, just how applicable data from waterspouts are to tornadoes, particularly to those in the strong and violent categories. The flow in the lowest levels of a waterspout, for example, may be different from that in a tornado, because a vortex over the ocean traverses a smoother surface and hence encounters less friction.

There is no substitute for direct observation of tornadoes, and since the late 1960's workers at the University of Oklahoma and the National Oceanic and Atmospheric Administration (NOAA) National Severe Storms Laboratory in Norman, Okla., have been systematically chasing tornadic thunderstorms in the hope of getting high-quality still and motion pictures that can be compared with radar observations and used to estimate wind speeds. Since 1981 Howard B. Bluestein and his students at the university have expanded this program by attempting to place a ground instrument package in the path of oncoming mesocyclones. The package, dubbed TOTO (not only for Dorothy's dog in *The Wizard of Oz* but also



ANNUAL TOTAL of tornadoes recorded in the U.S. shows a steady increase that is attributed to improved record keeping rather than to a real rise in frequency. The Federal Government began collecting tornado reports systematically in 1953 and has since extended its data base (maintained by the National Severe Storms Forecast Center in Kansas City, Mo.) back to 1950. Tornadoes are classified whenever possible according to the Fujita wind-speed scale as weak, strong or violent; since not all of them can be rated, the total is greater than the sum of the three categories. The increase in the total primarily reflects increased reporting of weak tornadoes. The number of strong and violent tornadoes, which are less likely to escape detection, shows little change. Fewer than 3 percent of all tornadoes are classified as violent, but they account for two-thirds of all tornado deaths; the peaks in the death curve reflect those in the violent-tornado curve.



WEEKLY AVERAGE of tornadoes recorded in the U.S. from 1950 to 1982 shows that most tornadoes (about 74 percent) strike between March and July. Most violent tornadoes and most deaths come in April, when the temperature contrast across the polar front is sharpest. Later the contrast is weaker, as are the resulting thunderstorms and tornadoes. The death figures are monthly averages for 1953–82.

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for Totable Tornado Observatory), was designed by A. J. Bedard, Jr., of the NOAA Wave Propagation Laboratory in Boulder, Colo.

TOTO is equipped to measure wind speed, wind direction, atmospheric pressure and temperature and electric field strength under the tornado cyclone. So far Bluestein and his colleagues have obtained data on a number of mesocyclones and have made at least one surprising finding: the pressure drop under a tornado cyclone is not as great as was expected, suggesting that the largest pressure drop is concentrated very close to the core.

Direct probing of the core above the ground may be possible with small rockets being developed by Stirling A. Colgate of the New Mexico Institute of Mining and Technology. The rockets are launched from a light plane at a distance of one to two kilometers from the tornado, and their instrument readings are radioed back to the plane. Preliminary launchings at waterspouts and two tornadoes have proved the concept, although further design work is required.

Doppler Systems

The greatest advances in understanding, however, are expected to come from the application of remote-sensing instrumentation: Doppler radar and its newer partner, Doppler lidar. Doppler systems measure the frequency shift between a transmitted microwave or light beam and its echoes from water droplets or dust particles in the atmosphere. The frequency is shifted upward if the target is moving toward the radar, downward if it is moving away and not at all if it is moving sideways. The wind-velocity component along the line of sight between the instrument and the target is thus proportional to the magnitude of the frequency shift.

Doppler-radar measurements made in the past decade have revealed the large-scale internal details of the flow within a thunderstorm. Mesocyclones in particular produce easily recognizable patterns on the radar screen, because their swirling high winds change direction over a small area. Most of what is known about the evolution of mesocyclones, such as the fact that rotation seems to begin in the mid-troposphere and then to build downward and upward, has come from Doppler radar. The usefulness of this instrument is currently limited by its spatial resolution: the received echoes, from which wind speed and other data are derived, are from a cylindrical region about 300 meters long and 175 meters in diameter along the radar beam. This means that while Doppler radar can easily gather information on the airflow in tornadic thunderstorms, it can just barely resolve the actual core regions of the largest tornadoes.

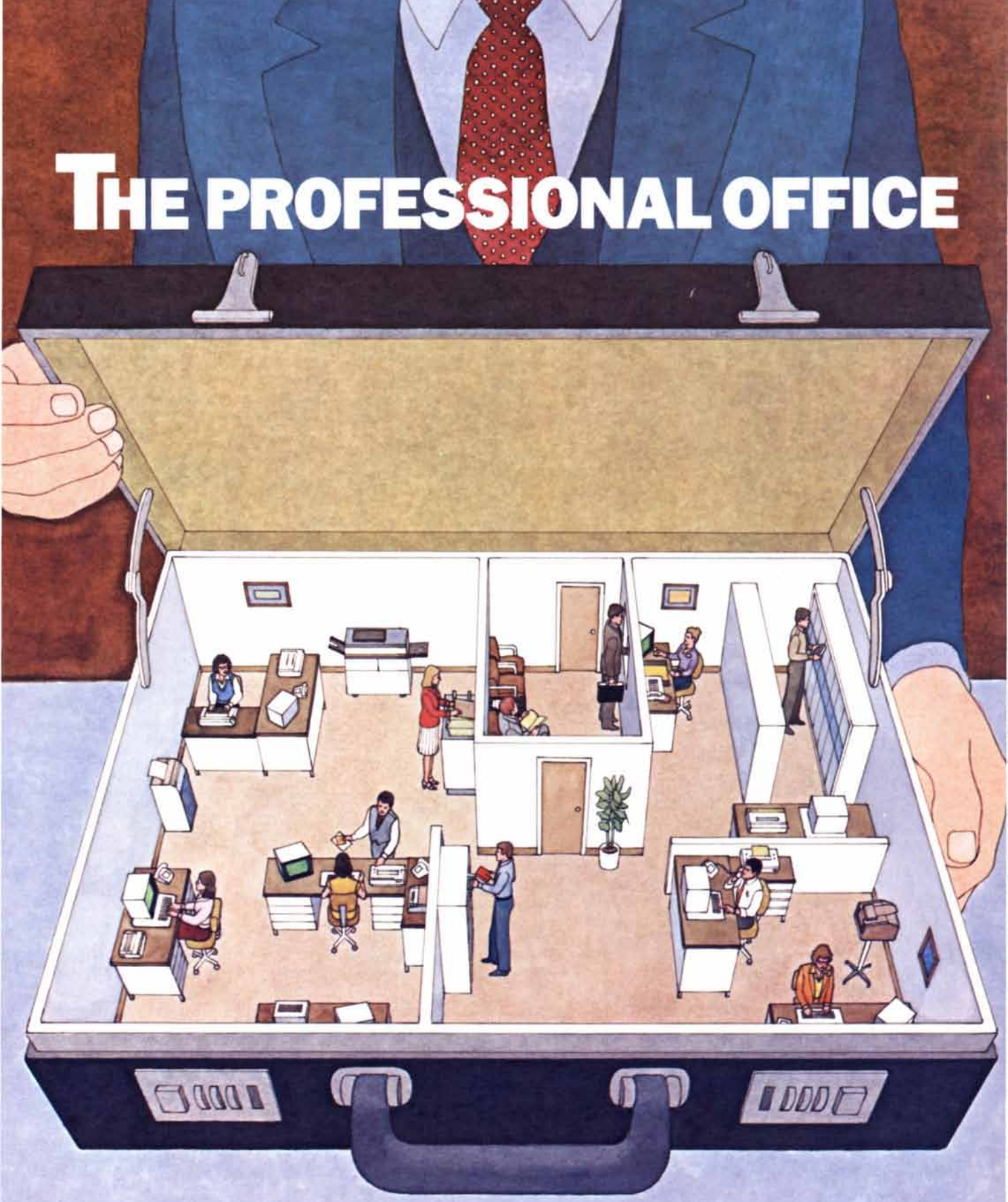
Dusan Zrnic and his associates at the Severe Storms Laboratory have developed special Doppler signal-processing techniques to obtain wind-speed data from giant tornadoes. A violent twister of this type, with a maximum funnel diameter of more than 1,600 meters, struck Binger, Okla., on May 22, 1981. Radar measurements showed that the funnel extended all the way to the top of the parent storm (an altitude of 12 kilometers), that it formed initially aloft and that it seemed to have a central downdraft (as might have been expected in a violent multiple-vortex tornado). Its wind speeds were measured at about 200 m.p.h.

Research groups at the Severe Storms Laboratory and at the National Center for Atmospheric Research in Boulder are trying to improve the resolution of Doppler radar to the point where it can image smaller tornadoes. The technology that may be best able to reveal the details of the core flow, however, is infrared Doppler lidar, which has a narrower beam (and hence a higher resolution) because of the shorter wavelength of infrared radiation. In recent years Ronald L. Schwiesow and his colleagues at the Wave Propagation Laboratory have tested a portable lidar unit on waterspouts, successfully measuring the core winds at various altitudes and distances from the center. Although at present there is no active effort to extend this work to tornadoes, it holds much promise for the future.

Forecasting tornadoes is even more difficult than understanding their dynamics, but the application of Doppler technology will soon bring improvements in this field as well. Partly because Doppler radar is so good at detecting mesocyclones, the National Weather Service plans to install Doppler units at many of its weather stations by the early 1990's. With the help of data from weather balloons and satellites, forecasters already have some success in mapping out, six to eight hours in advance, "watch" regions where strong thunderstorm activity is likely and tornado formation possible. The new radars will assist forecasters in picking out the few thunderstorms that might spawn tornadoes from the many that develop in a watch region. The result should be more reliable local tornado warnings, with fewer false alarms.

These warnings, however, will still come at most a half hour to an hour before a twister strikes. Because tornadoes are such localized phenomena and because their formation and behavior are controlled by so many variables, they are likely to remain to a large extent unpredictable. What recent developments in meteorological theory and observational technology suggest is that there is no reason for their behavior to remain a riddle.

THE PROFESSIONAL OFFICE



THE PROFESSIONAL OFFICE

During recent years, new automated procedures and machines, including technologically advanced communications systems, have been installed in large offices. Banks, insurers, securities dealers and other firms with clerical staffs frequently in excess of 1,000 have been major customers for office automation at the newest levels of technology. "We've had little choice but to learn how to use and manage this technology, and to take full advantage of it," says Cran Lawton, director of corporate communications at Aetna Life & Casualty in Hartford. "With tens of millions of claims to pay in a year, we've become heavily automated. IBM has been stationing people on-site here for a number of years, servicing our headquarters and our new computer facility in Middletown."

In the smaller offices essential to engineers and technicians, scientists, doctors and dentists, educators and administrators and some businesses, automation has lagged. One reason for this has been supply-side reluctance to devote marketing time and effort to smaller potential customers. As a result, some suppliers simply have no appropriate machinery to offer. Bob Lundquist of Eastman Kodak's office systems division explains, "Our systems are designed for medium- to high-volume users who receive as many as 7,000 incoming documents a day and who need about 20,000 photocopies a month." Another reason: uncertainty among professionals and small-office managers themselves. "I can't afford the time to change my whole system," a New England doctor said. "I don't know who I could depend on to operate a high-tech system. And I certainly can't risk losing a patient's records in the back of an electronic bottom drawer."

Yet the benefits of modern office systems are pervading offices regardless of size. "Office automation increases the professional's productivity 10- or 20-fold," says Mike Bell, director of planning and consulting services at Xerox. Bell cites Xerox's recent in-house study, "Office 88," which examines how businesses can effectively integrate automation technologies today and over the next five to 10 years. John O'Keefe, small business product group manager at Digital Equipment Corporation, agrees: "Productivity varies by business. But the improvements are really significant; the simplest word processing has a dramatic impact."

"If you don't get more productivity, then you're not capitalizing on technology," says "Duke" Sutherland, director of office automation programs in the office of the president at Wang Laboratories. "One of the traumas this office-automation business is going through is in trying to demonstrate cost efficiency. Businesses expect to be able to quantify the results of office automation. But we're also talking about qualitative improvements."

THE PROFESSIONAL OFFICE

The professional office has characteristics that distinguish it from larger, more broadly staffed offices. The professional's main stock-in-trade is his knowledge and the time to apply it. He is less able to postpone or delegate work than is his opposite number in trade or commerce. He is likely to work outside his office, at a construction site, a laboratory or a client consultation or while traveling. He is more likely to employ a secretary whose overall skills and experience are above average. And, more and more, "he" may be a "she."

The mechanization of office work has given rise to two specialized office structures useful to professionals: the "virtual" office and the "shared" office. Each has unique values, and the two may be combined.

Central to the functioning of any technologically advanced office is the work station, a term that comes from assembly-line manufacture, where a single worker maintains a fixed position with respect to his tools and the parts are conveyed to him. In a small office, a work station may require no more space than that formerly occupied by a telephone, typewriter, in-basket and telephone directory.

Wes Cantrell, president of Lanier Business Products of Atlanta, offers a checklist of concerns a professional should consider before installing a work-station-based office:

1. Can the work be automated?
2. If so, will automation be cost-effective?
3. If so, are documented programs, with adequate operator training, available for machinery and personnel?
4. Are suppliers of equipment and programs accessible and reliable?
5. Have other professionals with similar systems been contacted for their advice?

"Even a small business is a complex organization," Cantrell points out. "Still, if you don't learn how office automation can make you more productive, you will be at a disadvantage to those who do."

"Manufacturers of word-processing equipment offer training for one or two key or initial operators," advises Bill Brown, general manager of the Employer Services Division of ITT Educational Services of Indianapolis. "They haven't the facilities to train additional or subsequent operators, and training is not their main business function."

Brown's company, an ITT subsidiary, introduced its Employer Services division in 1981 to provide either generic or Wang-equipment-specific word-processing training programs. "It's a natural extension of the programs we've offered for technicians and operatives in fields from appliance repair to solar installation," Brown says. "We've seen, nationally, that the elusive 'good secretary' can and will benefit from this new equipment if properly trained. And all the technology in the world has little value without proper training."

THE VIRTUAL OFFICE

"Portable terminals and computers, equipped with appropriate software and facilities for communication..., create a 'virtual' office, which is essentially anywhere the worker happens to be," wrote V. E. Giuliano, senior member of the information-systems section of Arthur D. Little, in the September 1982 issue of *Scientific American*. "The remote work station... extends the range of places where written and numerical material can be generated, stored, retrieved, manipulated or communicated."

The Osborne, the first practical portable computer, weighed less than 30 pounds and proved popular enough to inspire competition. New firms such as Compaq and Gavilan, and veteran companies including Tandy, introduced varied, high-capacity products that made possible transportation of computer power among work stations, at a cost ranging from about $3,000 to half that amount. These devices made the virtual office possible, although the 30-pound weight of the microcomputer alone limited the range of all but the huskiest of professionals. Still, where limited range can sufficiently increase productivity, the high-capacity portable computer remains a desirable extension of the fixed office.

For example, Radio Shack Computer Centers, operated by Tandy Corporation of Dallas, offer a 26-pound portable computer, Model 4P, an expandable 64K machine with a nine-inch display screen and two 5 1/4-inch disk drives. Model 4P may be stored in airline overhead racks and can be used anywhere an AC outlet exists. It can connect to printers and telephone lines, and a fairly large number of programs are available. Without accessories, Model 4P costs $1800; complete

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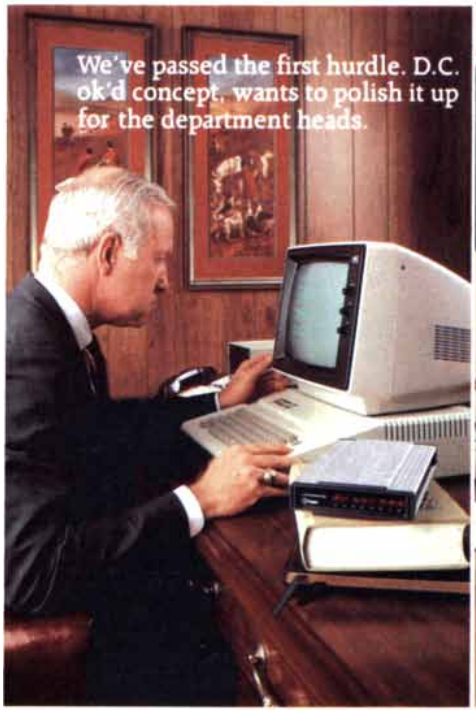

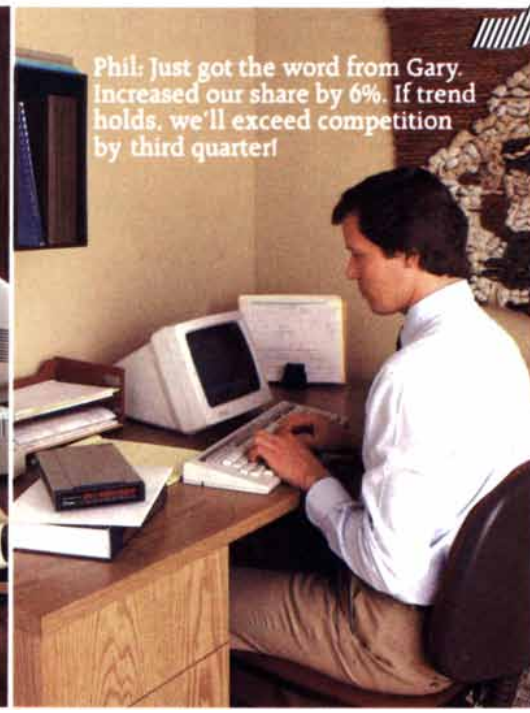

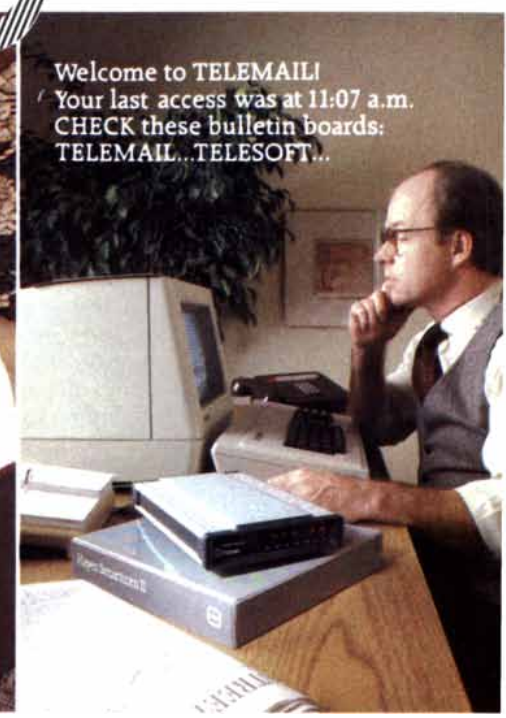

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The drive of personal/portable microcomputers has continued, and the miniaturization of machines unveiled during the past two years has made the virtual office possible for those requiring equipment truly light in weight. The new models are no larger than a desktop dictionary; they fit and carry comfortably in a small briefcase, and they can be battery-powered. As a rule they offer full-size keyboards, liquid crystal displays, communications capabilities and built-in programs, including word processing, accounting, and personal telephone and calendar systems. Epson recently introduced a "notebook computer" with a printing/graphic capability on paper the size of adding-machine tape. Hewlett-Packard's Model 75C has become popular with educators, who use the machine to prepare lecture material and record student grades and hence to be generally less "absent-minded" than their stereotype.

In an environment where professionals and managers "spend much of their time seeking information, traveling and attending meetings," as Mark Palmer says, the notebook computer is a quantum leap in efficiency. Palmer is manager of vertical marketing for Philips Information Systems of Dallas.

"Much depends on having the mental attitude to approach things in a different way," Palmer states. "There just isn't anything you can't do with these machines. But much depends on people's ability to use them, and their willingness to use them; many executives and professionals find it hard to create at the keyboard."

Ed Juge, Tandy's director of merchandising for business products, says Radio Shack's Model 100 "really spreads a person's wings. For about $1100, a professional owns a powerful computer, several useful programs, the tools to connect it to any telephone to send or receive information and even a custom-designed briefcase to carry it all in a space four inches deep."

One aspect of the virtual office that causes some professionals concern is that it involves the professional with certain information-management processes that he or she formerly delegated to a secretary. Less well understood is that in reality most virtual-office functions undertaken by professionals are those that would have been impossible, or very difficult, for a secretary to do.

Possibly the next dramatic development relating to the virtual office will be a rise in "telecommuting," as professionals and others who have no reason to travel to their offices on a given day except to deal with paperwork choose to deal with it from home. Certainly the need for totally dependable, very swift, easily available local and intercity telephone service will grow sharply even from its current high level. And the electronic distancing of workers from the offices they have traditionally occupied may cause psychological effects stemming from the unwelcome separation from co-workers or supervisors, or from unexpected contact with customers and clients.

THE SHARED OFFICE

Communal or cooperative use of real estate by distinct and separate business organizations is as common today as the indoor shopping mall or the hospital-connected medical or dental center. A shopping mall, of course, is often populated by small businesses whose "back-office" needs are as different as the products and services they offer for public consideration in their retail displays. Professional offices share many "back-office" similarities. An oral surgeon and a pediatrician have like needs for patient X-ray and record storage. Both charge for office visits, consultations and specific professional procedures done. Both may use a laboratory or pharmacy in common. And each may feel a need for expensive office-automation equipment that might feature capacity in excess of need. For these professionals, as for others in branches of medicine such as veterinary or psychiatry, the modern work-station-based shared office has much to offer.

"The electronic typewriter, with its speed and its memory capability, has been a good transition machine to word processing," states Phil Reed, vice president of operations for BusinessLand, a San Jose retail computer store. The standard QWERTY keyboard arrangement has been preserved in most word-processing equipment. Such a keyboard is considered "user-friendly," a term describing any computer operation that is performed with skills or knowledge learned in a non computer environment. New technology in computing is focusing on the way the keyboard interacts with the work station display screen. Apple Computer's Lisa and MacIntosh machines now use a "mouse," similar to the planchet of an Ouija board, to indicate the point on the display where the next operation is to commence. Hewlett-Packard's new HP-150 line of personal computers includes a touch-screen facility through which users may direct their machines with their fingertips.

"The transformation to the automated office will not come about until the systems are very easy to use," says Kathryn Nune of Apple Computer. CPT's Jerry Jenko is confident it's a generation gap, "a short-term phenomenon. The up-and-coming work force is well trained. Younger people know how to use these machines and ask for them."

Xerox has developed a sophisticated "electronic desktop" work station for professionals called the Xerox 8010 Star Information System, which combines computing, text editing, graphics creation and communications. Its "user-friendliness" is suggested by the fact that a professional need use just the "mouse" and four main function keys to store and retrieve information, print, send electronic mail, draw and even check spelling. According to Dr. Robert Spinrad, a director of technology at Xerox's Palo Alto Research Center, the 8010 represents Xerox's attempt to automate the knowledge worker.

Within the confines of the professional office, such a system as Xerox's 8010 Star may contain all the useful automating elements. In the shared office, such a system must be cable-linked to other systems. Xerox has developed a network for this purpose, called Ethernet: it operates at high speed, connects different work stations and allows access to centrally located mass storage files, a printer and electronic and other mail facilities.

In operation, the system might function as follows: a professional or secretary reports to work, pours a cup of coffee and turns on the work station equipment. Its screen reports on the status of the office. It indicates that mail has been received and can indicate that mail received on a prior day still needs to be picked up. It displays telephone messages received and recorded since the prior day's close of business. It presents a list of appointments or meetings scheduled for the day. It lists items that had been marked for follow-up. Its displays are designed to resemble the items they represent: symbols or "icons" on the screen are file drawers, printers, in-baskets, documents and folders.

"These symbols replace their physical counterparts," says Don Ramsay, manager of public relations for Xerox's western operations in El Segundo, California. "For example, instead of walking to a file cabinet, finding the item wanted and returning to the desk to look at it, the user 'opens' the elec-

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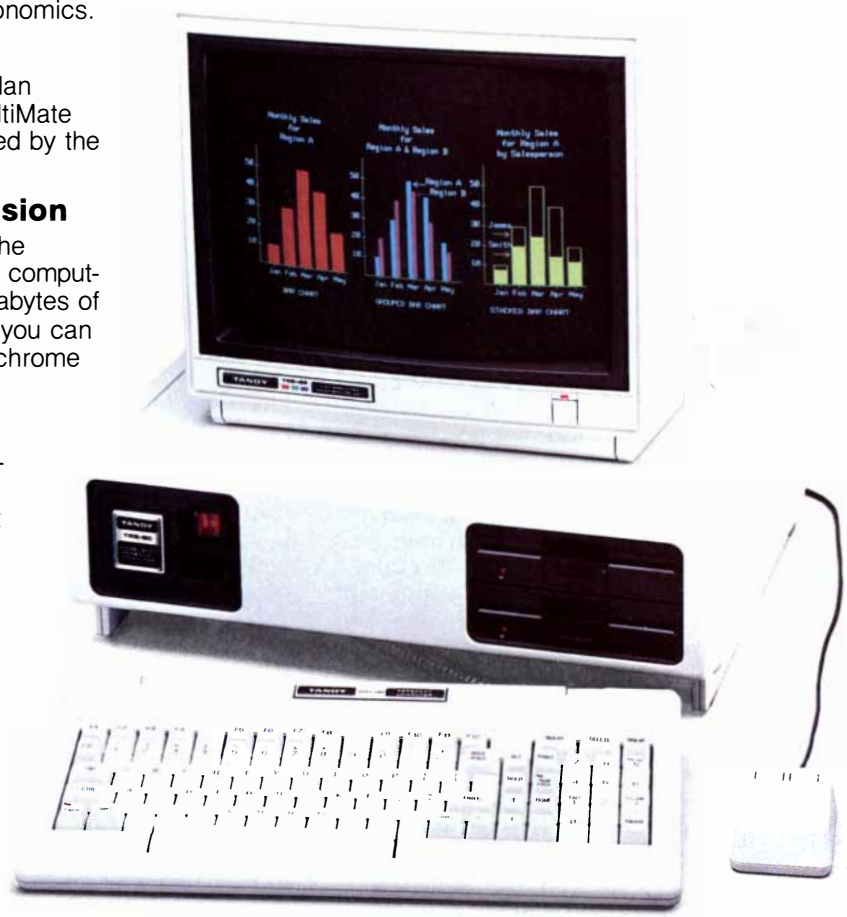

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Price Comparison†	Tandy 2000	IBM Personal Computer
Base Unit	$2750	$2104
2nd Drive	Included (720K)	$529 (320K)
Monochrome Monitor	$249	$345
Display/Printer Adapter	Included	$335
128K RAM	Included	$165
RS-232	Included	$120
MS-DOS 2.0	Included	$60
Total Cost*	$2999	$3658
Feature Description	**Tandy 2000**	**IBM Personal Computer**
Internal Memory	128K Standard	64K Standard
Disk Capacity Per Drive	720K	160K or 320K (optional)
Microprocessor Clock Speed	8 MHz	4.7 MHz
True 16-Bit Microprocessor	Yes (80186) 16-bit/16-bit data path	No (8088) 16-bit/8-bit data path
User-Available Expansion Slots*	4	2
Graphics Options		
Color Resolution	640 x 400	320 x 200
Number of Colors	8	4
Monochrome Resolution	640 x 400	640 x 200

*Comparable IBM configuration with monochrome adapter and display, communications adapter, two 320K disk drives and 128K RAM
†Manufacturer's pricing as of 9/1/83

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tronic file drawer by moving the screen pointer to it and pressing a key. All the contents of the file are listed on the screen; as many as six may be selected and displayed at the same time."

In the context of an office shared by medical professionals, a Star-Ethernet system could allow common invoicing and mailing, printer use, mail receiving and opening, receipt of laboratory test reports and filing. The system could streamline patient reception and even coordinate building security and utilities. Apart from the accuracy and reliability of such common usage, it enables office personnel to concentrate on work where they can add maximum economic value.

"It's our role as a company to apply office systems to the productivity needs of any company or profession in the country," says John Shoch, president of Xerox's office systems division. "That has to include support for questions and problems that may arise. It has to mean service, training and support ranging from an in-office call to a seminar at our Xerox Learning Systems campus in Leesburg, Virginia.

"There are more office-equipment suppliers now than I can name. But few are prepared to invest in long-range service and support. Many wouldn't even know how.

"Even within a single office structure, professionals are diverse and need competency ranging from a single electric typewriter, at one level, to a sophisticated work-station-based system at the other. Only when that competency exists can the activities of such diverse individuals be productively leveraged. Ensuring service and support is where we come in—and stay in."

THE COMMUNICATIONS LIFELINE

Work-station-based virtual and shared offices greatly increase the professional's need for dependable communications equipment and services. It is at the communications level that computer technology merges with telecommunications technology, and an explosion of products, services and systems for computer communications is occurring. "If low capacity bottlenecks the growth of telecomputing, then the cases of use and capacity will not be there," said Dennis Hayes, president of Hayes Microcomputer Products of Norcross, Georgia, in a 1983 interview in *Personal Computing* magazine. "The customer will be less satisfied and will turn away from the concept of telecomputing."

The process of communication access begins, in equipment terms, with a modem. This device converts signals generated in a computer into different signals that can be transmitted across telephone lines (and reconverted, at the other end, by a receiving modem). Although the types of modems are varied, it is the quality of the modem that can directly affect the reliability and accessibility of every level of communication among work stations.

Hayes's own product, the "Smartmodem," fits comfortably under a conventional telephone. Other models may be installed within a computer and connected directly and permanently to telephone lines.

Beyond the modem lie realms of verbal and nonverbal communication. Texas Instruments and other firms are developing speech-recognition and voice store-and-forward features. Wang's Duke Sutherland, through the firm's Advanced Systems Laboratory, is working on products that build on studies indicating that professionals do not want to replace verbal communication.

Giving and getting productive communication is the purpose of office automation. "Showing a secretary how to type 10 percent faster is not an interesting improvement to us," says Xerox executive John Shoch. "Take a grant proposal, for example. Formerly, a professional—the source of the proposal—would outline and define it and then involve several people in its completion and production. That system was complex and burdensome; if you charted it, it would have many feedback loops and could take seven working days. Now the tools are closer to the originator. The proposal can be written or dictated by the professional, quickly polished and formatted, laser-printed and even electronically submitted. It can be complete in one day. That's a 700 percent improvement—and that's the magnitude of improved productivity we design systems for."

Some data communications network firms have expanded to provide "information utility" services. GTE's Telenet Group has, in conjunction with the American Medical Association, developed a medical information network called MINET to help doctors find specific medical facts quickly. The group, based in Vienna, Virginia, has grown to well over $100 million in sales in less than five years. ITT Dialcom, in Silver Spring, Maryland, has just announced an expansion of its own electronic mail system to include access to documents and information from the American Bar Association. "Our electronic mail service, already used by the Department of Agriculture, the EPA, and the FDA, has just been installed as well in the White House," says spokesperson Paul Warren. ITT Dialcom is part of ITT's Communications and Information Services Group.

Bill Buehler is vice president for market planning at AT&T Information Systems, which opened for business in January, 1983. The firm recently introduced MERLIN, a "smart telephone" designed expressly for small businesses and professions. "MERLIN's design allows features to be programmed on individual phones by plugging in a cartridge," Buehler states. All aspects of conventional telephone communication are streamlined in the MERLIN system, including hold, intercom, line selection and conferencing. The Morristown, New Jersey, firm will be introducing new features to further expand its microprocessor-based telephones. A separate system, called DIMENSION AIS System 85, provides an electronic office communications capability. It was designed by Bell Laboratories and is manufactured in Denver by Western Electric.

The Source, a major information utility based in Virginia, offers a conferencing system called Participate, designed and operated by Participation Systems of Winchester, Massachusetts. A professional who subscribes to The Source may start a conference electronically, and within days involve hundreds of other interested subscribers. Xerox's Mike Bell is one of many advocates of the new system.

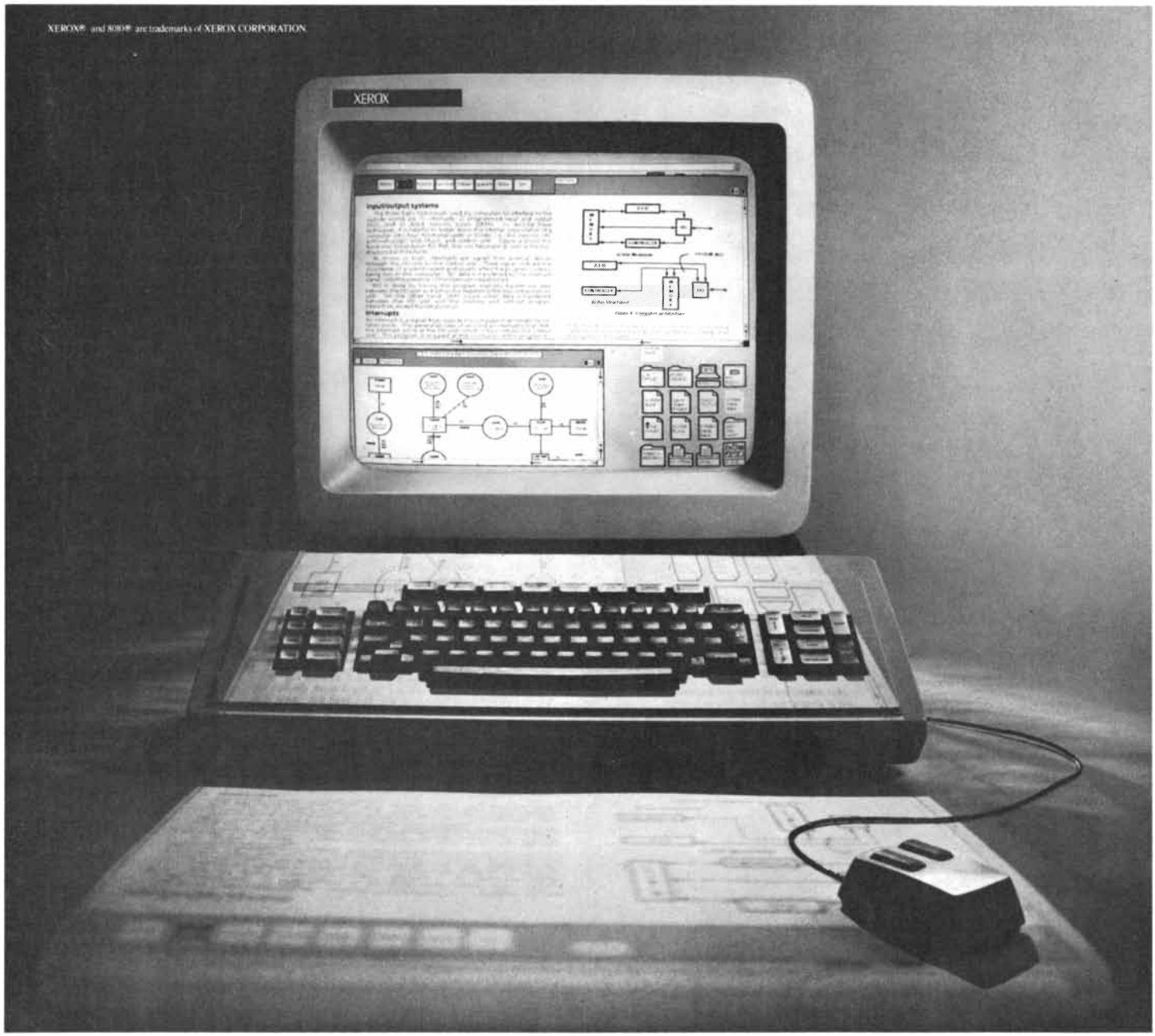
"The Participate system gives the smaller or professional office large-office features. In a large company, one can walk down the hall and pull a group together for a discussion. Participate replaces the hall."

There are electronic "bottom drawers" where office data may be lost. The automated professional office, complete with state-of-the-art computers, printers, communicators and the like, still cannot think. But the opportunities for dramatic increases in productivity exist and are expanding, and they are accessible to professionals and small-business managers.

"The Professional Office" was written by Peter J. Brennan and produced by Development Counsellors International, Ltd., of New York. Artwork/graphics: Sherin & Matejka, Inc., with acknowledgment to Xerox Corp., Office Systems Division.

The Star of Team Xerox.

XEROX



The Star 8010 professional workstation has always been known as a computer of dazzling capabilities, especially in its graphics, information processing and document preparation.

Team Xerox

But what some people may not know is that the Star is also the key element in Team Xerox, a system of office machines designed to work together like a team.

When part of an Ethernet network, the Star can work with a wide array of word processors, mainframes, personal and business computers, printers, electronic mail and file services, facsimile terminals, communicating Memorywriters, other networks and, of course, other Stars. It also provides 3270 and TTY emulation.

Its full 17″ bit-mapped screen lets you view two full pages simultaneously and open up to six documents at a time without covering up a previous document.

It's also the only workstation that can create and print documents in more than a dozen languages, including Russian and, for the first time, Japanese (Katakana, Hiragana and Kanji).

While other workstations may use Xerox innovations like the mouse, icons, windows, property sheets and combined text and graphics, the Star simply does more with them.

For example, the Star's extensive software is fully integrated, to allow you to work with text and graphics simultaneously. You can draw a flowchart right in the middle of a full page of text without having to resort to a separate program and limited buffer "scratchpad" or "clipboard."

In terms of capabilities, ease of use and overall value, the Star would have to be considered the stellar workstation in the industry.

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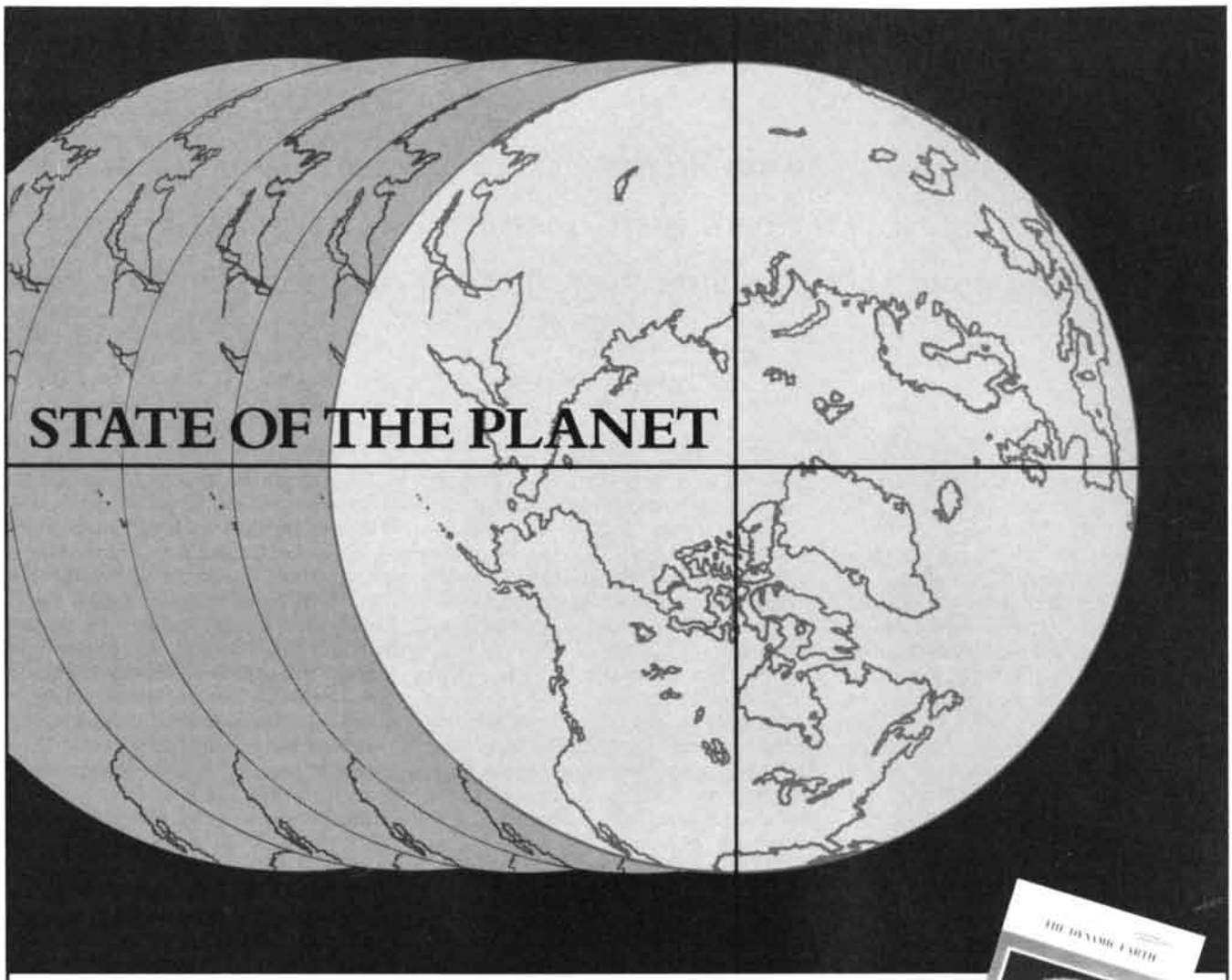

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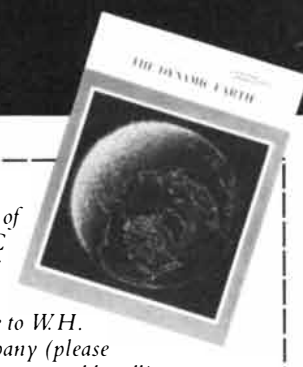

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Vision by Man and Machine

How does an animal see? How might a computer do it? A study of stereo vision guides research on both these questions. Brain science suggests computer programs; the computer suggests what to look for in the brain

by Tomaso Poggio

The development of computers of increasing power and sophistication often stimulates comparisons between them and the human brain, and these comparisons are becoming more earnest as computers are applied more and more to tasks formerly associated with essentially human activities and capabilities. Indeed, it is widely expected that a coming generation of computers and robots will have sensory, motor and even "intellectual" skills closely resembling our own. How might such machines be designed? Can our rapidly growing knowledge of the human brain be a guide? And at the same time can our advances in "artificial intelligence" help us to understand the brain?

At the level of their hardware (the brain's or a computer's) the differences are great. The neurons, or nerve cells, in a brain are small, delicate structures bound by a complex membrane and closely packed in a medium of supporting cells that control a complex and probably quite variable chemical environment. They are very unlike the wires and etched crystals of semiconducting materials on which computers are based. In the organization of the hardware the differences also are great. The connections between neurons are very numerous (any one neuron may receive many thousands of inputs) and are distributed in three dimensions. In a computer the wires linking circuit components are limited by present-day solid-state technology to a relatively small number arranged more or less two-dimensionally.

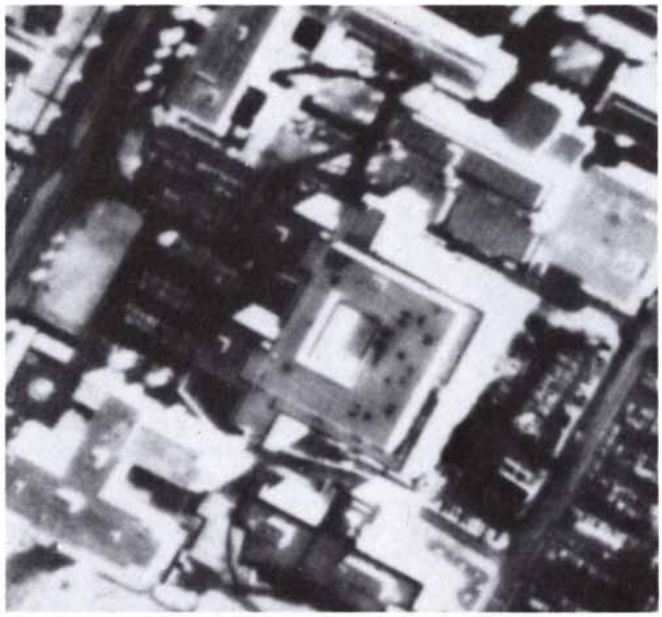
In the transmission of signals the differences again are great. The binary (on-off) electric pulses of the computer are mirrored to some extent in the all-or-nothing signal conducted along nerve fibers, but in addition the brain employs graded electrical signals, chemical messenger substances and the transport of ions. In temporal organization the differences are immense. Computers process information serially (one step at a time) but at a very fast rate. The time course of their operation is governed by a computer-wide clock. What is known of the brain suggests that it functions much slower but that it analyzes information along millions of channels concurrently without need of clock-driven operation.

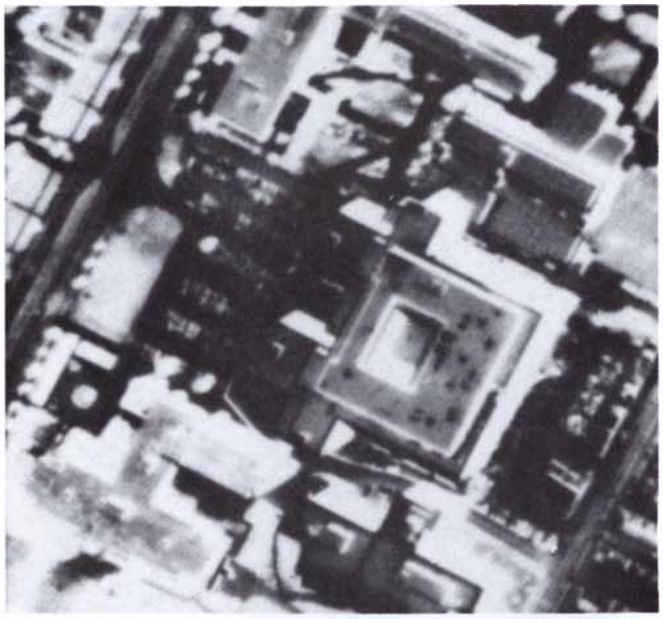
How, then, are brains and computers alike? Clearly there must be a level at which any two mechanisms can be compared. One can compare the tasks they do. "To bring the good news from Ghent to Aix" is a description of a task that can be done by satellite, telegraph, horseback messenger or pigeon post equally well (unless other constraints such as time are specified). If, therefore, we assert that brains and computers function as information-processing systems, we can develop descriptions of the tasks they perform that will be equally applicable to either. We shall have a common language in which to discuss them: the language of information processing. Note that in this language descriptions of tasks are decoupled from descriptions of the hardware that perform them. This separability is at the foundation of the science of artificial intelligence. Its goals are to make computers more useful by endowing them with "intelligent" capabilities, and beyond that to understand the principles that make intelligence possible.

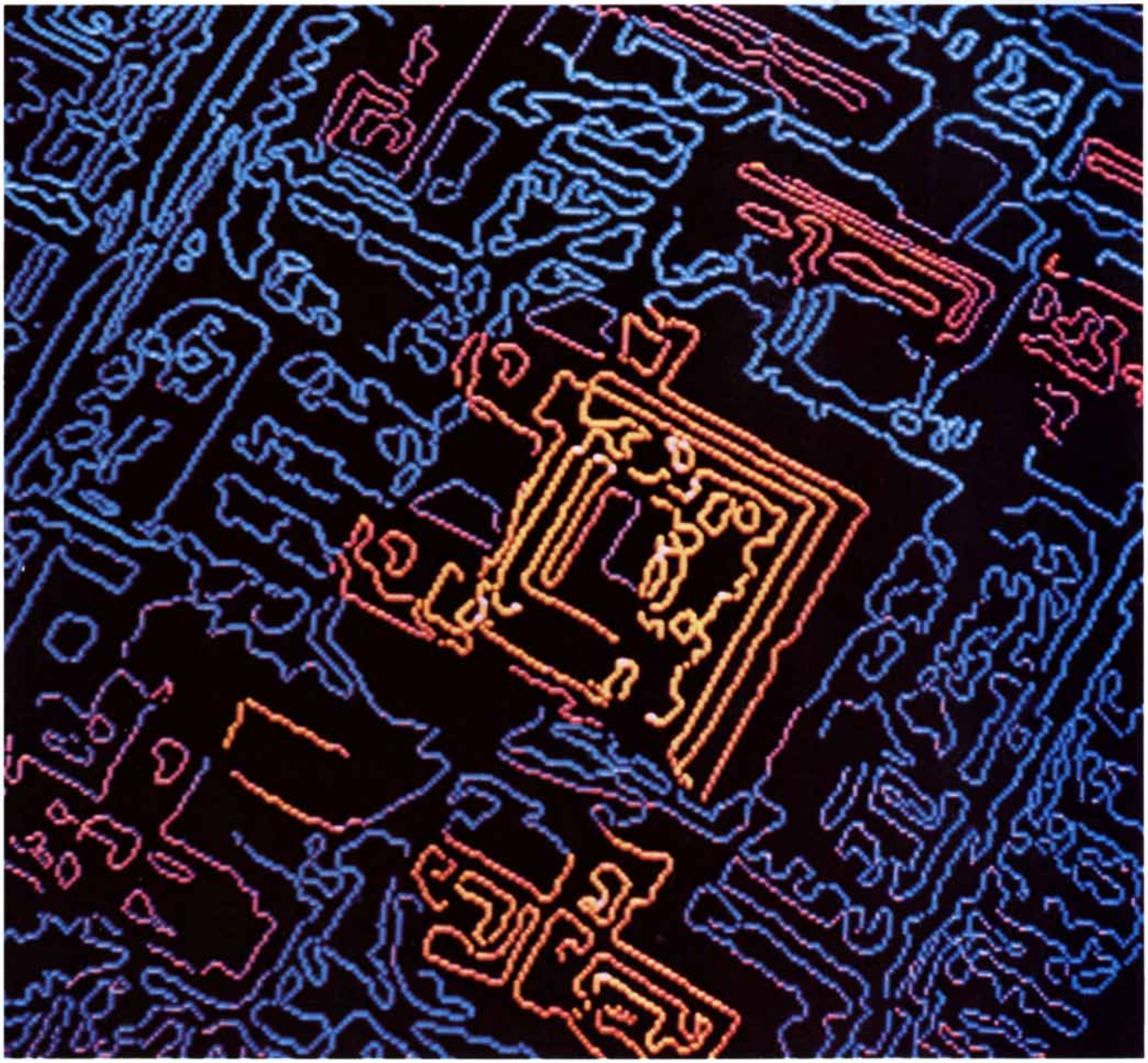
In no field have the descriptions of information-processing tasks been more precisely formulated than in the study of vision. On the one hand it is the dominant sensory modality of human beings. If we want to create robots capable of performing complex manipulative tasks in a changing environment, we must surely endow them with adequate visual powers. Yet vision remains elusive. It is something we are good at; the brain does it rapidly and easily. It is nonetheless a mammoth information-processing task. If it required a conscious effort, like adding numbers in our head, we would not undervalue its difficulty. Instead we are easily lured into oversimple, noncomputational preconceptions of what vision really entails.

Ultimately, of course, one wants to know how vision is performed by the biological hardware of neurons and their synaptic interconnections. But vision is not exclusively a problem in anatomy and physiology: how nerve cells are interconnected and how they act. From the perspective of information processing (by the brain or by a computer) it is a problem at many levels: the level of computation (What computational tasks must a visual system perform?), the level of algorithm (What sequence of steps completes the task?) and then the level of hardware (How might neu-

STEREO VISION BY A COMPUTER exemplifies the study of vision as a problem in information processing. The images at the top of the opposite page are aerial photographs provided by Robert J. Woodham of the University of British Columbia. They show part of the university's campus. In two ways they mimic the visual data on which biological vision is based. First, they were made from different angles, so that objects in one image have a slightly different position in the other. The two eyes of human beings also see the world from different angles. Second, the images were made by a mosaic of microelectronic sensors, each of which measures the intensity of light along a particular line of sight. The photoreceptor cells of the eye do much the same thing. The map at the bottom was generated by a computer programmed to follow an algorithm, or procedure, devised by David Marr and the author at the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology and further developed there by W. Eric L. Grimson. The computer filtered the images to emphasize spatial changes in intensity. Then it performed stereopsis: it matched features from one image to the other, determined the disparity between their positions and calculated their relative depths in the three-dimensional world. Increasing elevations in the map are coded in colors from blue to red.







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219	213	215	215	205	215	222	161	135	141	128	129	131	128	125	128	127

BEGINNING OF VISION for an animal or a computer is a gray-level array: a point-by-point representation of the intensity of light produced by a grid of detectors in the eye or in a digital camera. The image at the top of this illustration is such an array. It was produced by a digital camera as a set of intensity values in a grid of 576 by 454 picture elements ("pixels"). Intensity values for the part of the image inside the rectangle are given digitally at the bottom.

rons or electronic circuits execute the algorithm?). Thus an attack on the problem of vision requires a variety of aids, including psychophysical evidence (that is, knowledge of how well people can see) and neurophysiological data (knowledge of what neurons can do). Finding workable algorithms is the most critical part of the project, because algorithms are constrained both by the computation and by the available hardware.

Here I shall outline an effort in which I am involved, one that explores a sequence of algorithms first to extract information, notably edges, or pronounced contours in the intensity of light, from visual images and then to calculate from those edges the depths of objects in the three-dimensional world. I shall concentrate on a particular aspect of the task, namely stereopsis, or stereo vision. Not the least of my reasons is the central role stereopsis has played in the work on vision that my colleagues and I have done at the Artificial Intelligence Laboratory of the Massachusetts Institute of Technology. In particular, stereopsis has stimulated a close investigation of the very first steps in visual information processing. Then too, stereopsis is deceptively simple. As with so many other tasks that the brain performs without effort, the development of an automatic system with stereo vision has proved to be surprisingly difficult. Finally, the study of stereopsis benefits from the availability of a large body of psychophysical evidence that defines and constrains the problem.

The information available at the outset of the process of vision is a two-dimensional array of measurements of the amount of light reflected into the eye or into a camera from points on the surfaces of objects in the three-dimensional visual world. In the human eye the measurements are made by photoreceptors (rod cells and cone cells), of which there are more than 100 million. In a camera that my colleagues and I use at the Artificial Intelligence Laboratory the processes are different but the result is much the same. There the measurements are made by solid-state electronic sensors. They produce an array of 1,000 by 1,000 light-intensity values. Each value is a pixel, or picture element.

In either case it is inconceivable that the gap between the raw image (the large array of numbers produced by the eye or the camera) and vision (knowing *what* is around, and *where*) can be spanned in a single step. One concludes that vision requires various processes—one thinks of them as modules—operating in parallel on raw images and producing intermediate representations of the images on which other processes can work. For example, several vision modules seem to be involved in reconstruct-

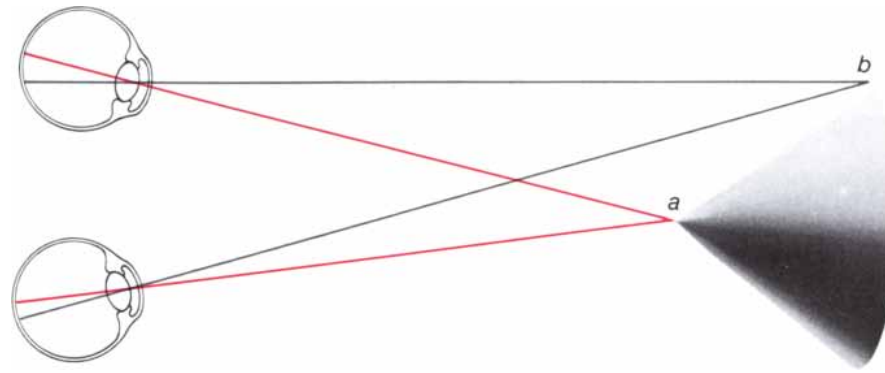
ing the three-dimensional geometry of the world. A short list of such modules would have to include modules that deduce shape from shading, from visual texture, from motion, from contours, from occlusions and from stereopsis. Some may work directly on the raw image (the intensity measurements). Often, however, a module may operate more effectively on an intermediate representation.

Stereopsis arises from the fact that our two eyes view the visual world from slightly different angles. To put it another way, the eyes converge slightly, so that their axes of vision meet at a point in the visual world. The point is said to be fixated by the eyes, that is, the image of the point falls on the center of vision of each retina. Any neighboring point in the visual field will then project to a point on each retina some distance from the center of vision. In general this distance will not be the same for both eyes. In fact, the disparity in distance will vary with the depth of the point in the visual field with respect to the fixated point.

Stereopsis, then, is the decoding of three-dimensionality from binocular disparities. It might appear at first to be a straightforward problem in trigonometry. One might therefore be tempted to program a computer to solve it that way. The effort would fail; our own facility with stereopsis has led us to gloss over the central difficulty of the task, as we may see if we formally set out the steps involved in the task. They are four: A location in space must be selected from one retinal image. The same location must be identified in the other retinal image. Their positions must be measured. From the disparity between the two measurements the distance to the location must be calculated.

The last two steps are indeed an exercise in trigonometry (at least in the cases considered in this article). The first two steps are different. They require, in effect, that the projection of the same point in the physical world be found in each eye. A group of contiguous photoreceptors in one eye can be thought of as looking along a line of sight to a patch of the surface of some object. The photoreceptors looking at the same patch of surface from the opposite eye must then be identified. Because of binocular disparity they will not be at the same position with respect to the center of vision.

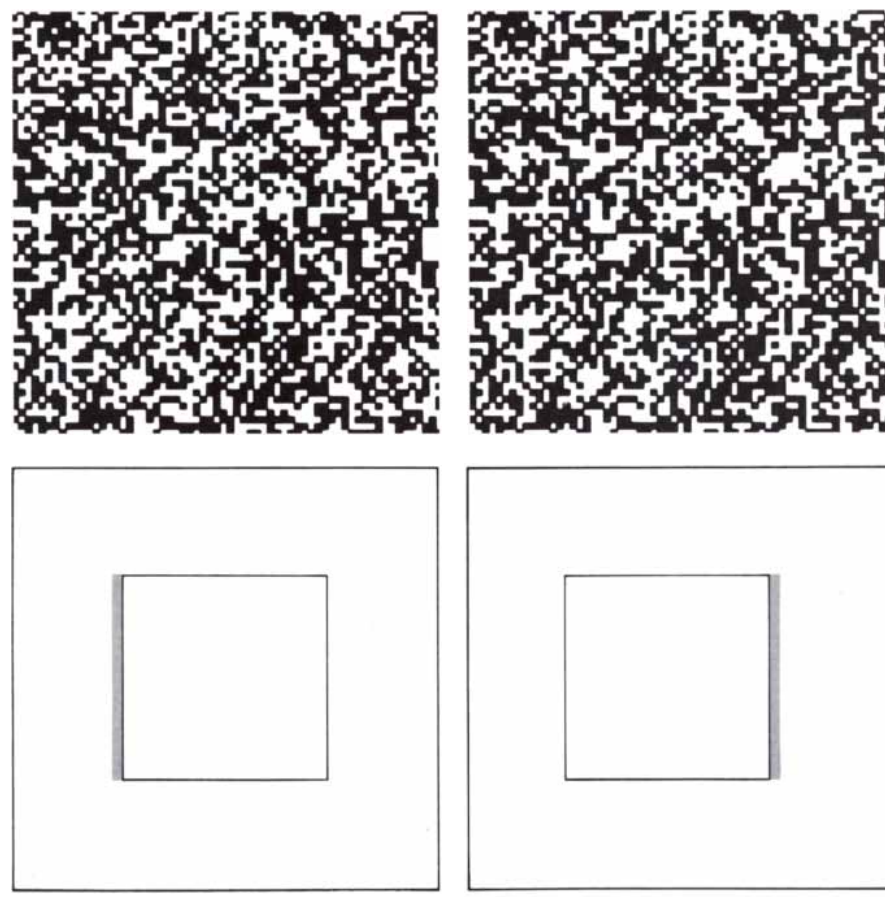
This, of course, is where the difficulty lies. For us the visual world contains surfaces that seem effectively labeled because they belong to distinct shapes in specific spatial relations to one another. One must remember, however, that vision begins with no more than arrays of raw light intensity measured from point to point. Could it be that the brain



BINOCULAR DISPARITIES are the basis for stereopsis. They arise because the eyes converge slightly, so that their axes of vision meet at a point in the external world (*a*). The point is "fixated." A neighboring point in the world (*b*) will then project to a point on the retina some distance from the center of vision. The distance will not be the same for each eye.

matches patterns of raw light intensity from one eye to the other? Probably not. Experiments with computers place limits on the effectiveness of the matching, and physiological and psychophysical evidence speaks against it for the human visual system. For one thing, a given patch of surface will not necessarily reflect the same intensity of light to both eyes. More important, patches of surface widely separated in the visual world may happen to have the same intensity. Matching such patches would be incorrect.

A discovery made at AT&T Bell Laboratories by Bela Julesz shows the full extent of the problem. Julesz devised pairs of what he called random-dot stereograms. They are visual stimuli that contain no perceptual clues except bin-



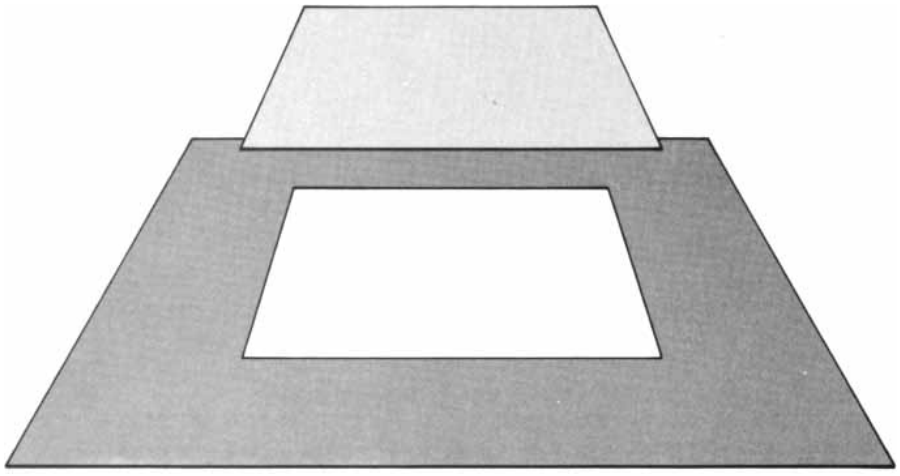
RANDOM-DOT STEREOGRAMS devised by Bela Julesz of AT&T Bell Laboratories are visual textures containing no clues for stereo vision except binocular disparities. The stereograms themselves are the same random texture of black and white dots (*top*). In one of them, however, a square of the texture is shifted toward the left; in the other it is shifted toward the right (*bottom*). The resulting hole in each image is filled with more random dots (*gray areas*).

ocular disparities. To make each pair he generated a random texture of black and white dots and made two copies of it. In one of the copies he shifted an area of the pattern, say a square. In the other copy he shifted the square in the opposite direction. He filled the resulting hole in each pattern with more random texture. Viewed one at a time each such pattern looked uniformly random. Viewed through a stereoscope, so that each eye saw one of the patterns and the brain could fuse the two, the result was startling. The square gave a vivid impression of floating in front of its surroundings or behind them. Evidently stereopsis does not require the prior perception of objects or the recognition of shapes.

Julesz' discovery enables one to formulate the computational goal of stereopsis: it is the extraction of binocular disparities from a pair of images without the need for obvious monocular clues. In addition the discovery enables one to formulate the computational problem inherent in stereopsis. It is the correspondence problem: the matching of elements in the two images that correspond to the same location in space without the recognition of objects or their parts. In random-dot stereograms the black dots in each image are all the same: they have the same size, the same shape and the same brightness. Any one of them could in principle be matched with any one of a great number of dots in the other image. And yet the brain solves this false-target dilemma: it consistently chooses only the correct set of matches.

It must use more than the dots themselves. In particular, the fact that the brain can solve the correspondence problem shows it exploits a set of implicit assumptions about the visual world, assumptions that constrain the correspondence problem, making it determined and solvable. In 1976 David Marr and I, working at M.I.T., found that simple properties of physical surfaces could limit the problem sufficiently for the stereopsis algorithms (procedures to be followed by a computer) we were then investigating. These are, first, that a given point on a physical surface has only one three-dimensional location at any given time and, second, that physical objects are cohesive and usually are opaque, so that the variation in depth over a surface is generally smooth, with discontinuous changes occurring only at boundary lines. The first of these constraints—uniqueness of location—means that each item in either image (say each dot in a random-dot stereogram) has a unique disparity and can be matched with no more than one item in the other image. The second constraint—continuity and opacity—means that disparity varies smoothly except at object boundaries.

Together the two constraints provide matching rules that are reasonable and powerful. I shall describe some simple ones below. Before that, however, it is necessary to specify the items to be matched. After all, the visual world is not a random-dot stereogram, consisting only of black and white dots. We have already seen that intensity values are too unreliable. Yet the information the brain requires is encrypted in the intensity array provided by photoreceptors. If an additional property of physical surfaces is invoked, the problem is simplified. It is based on the observation that at places where there are physical changes in a surface, the image of the surface usually shows sharp variations in intensity. These variations (caused by markings on a surface and by variations in its depth) would be more reliable tokens for matching than raw intensities would be.



VIVID PERCEPTION OF DEPTH results when the random-dot stereograms shown in the bottom illustration on the preceding page are viewed through a stereoscope, so that each eye sees one of the pair and the brain can fuse the two. The sight of part of the image "floating" establishes that stereopsis does not require the recognition of objects in the visual world.

Instead of raw numerical values of intensity, therefore, one seeks a more symbolic, compact and robust representation of the visual world: a description of the world in which the primitive symbols—the signs in which the visual world is coded—are intensity variations. Marr called it a "primal sketch." In essence it is the conversion of the gray-level arrays provided by the visual photoreceptors into a form that makes explicit the position, direction, scale and magnitude of significant light-intensity gradients, with which the brain's stereopsis module can solve the correspondence problem and reconstruct the three-dimensional geometry of the visual world. I shall describe a scheme we have been using at the Artificial Intelligence Laboratory for the past few years, based on old and new ideas developed by a number of investigators, primarily Marr, Ellen C. Hildreth and me. It has several attractive features: it is fairly simple, it works well and it shows interesting resemblances to biological vision, which, in fact, suggested it. It is not, however, the full solution. Perhaps it is best seen as a working hypothesis about vision.

Basically the changes of intensity in an image can be detected by comparing neighboring intensity values in the image: if the difference between them is great, the intensity is changing rapidly. In mathematical terms the operation amounts to taking the first derivative. (The first derivative is simply the rate of change of a mathematical function. Here it is simply the rate at which intensity changes on a path across the gray-level array.) The position of an extremal value—a peak or a pit—in the first derivative turns out to localize the position of an intensity edge quite well [*see illustration on opposite page*]. In turn the intensity edge often corresponds to an edge on a physical surface. The second derivative also serves well. It is simply the rate of change of the rate of change and is obtained by taking differences between neighboring values of the first derivative. In the second derivative an intensity edge in the gray-level array corresponds to a zero-crossing: a place where the second derivative crosses zero as it falls from positive values to negative values or rises from negative values to positive.

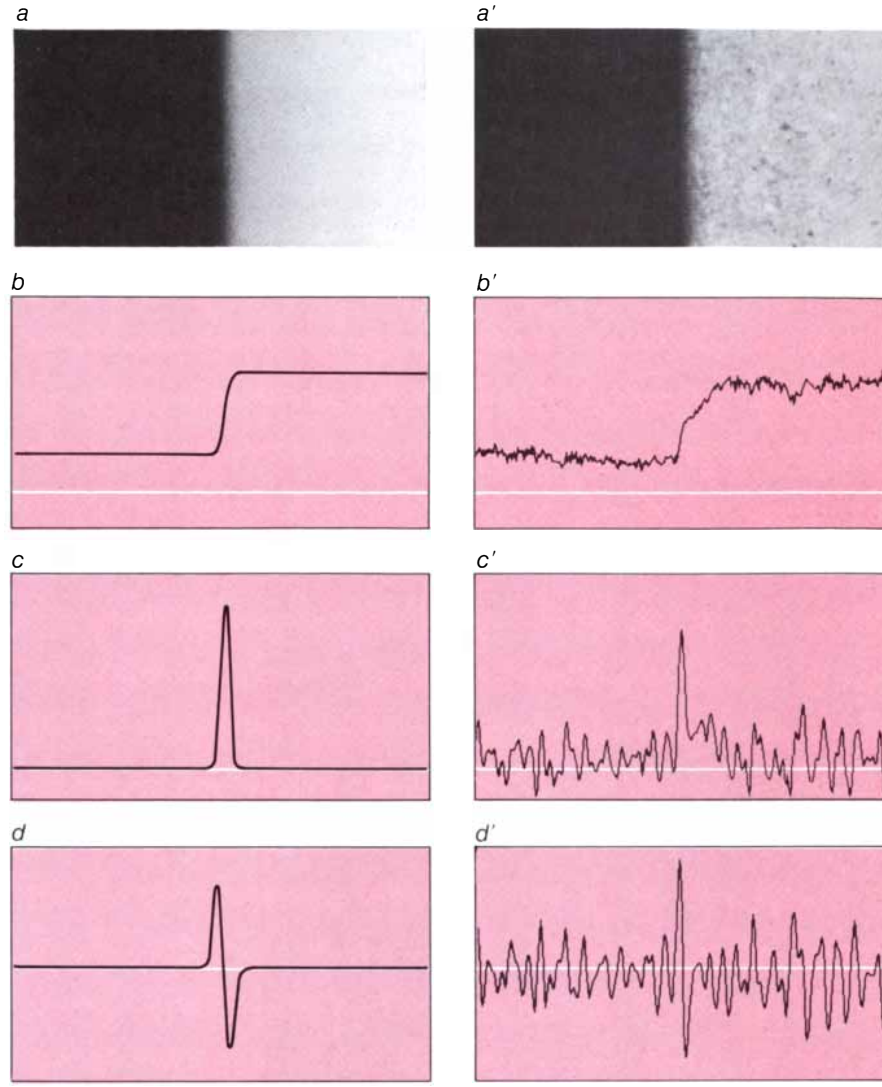
Derivatives seem quite promising. Used alone, however, they seldom work on a real image, largely because the intensity changes in a real image are rarely clean and sharp changes from one intensity value to another. For one thing, many different changes, slow and fast, often overlap on a variety of different spatial scales. In addition changes in intensity are often corrupted by the visual analogue of noise. They are corrupted, in other words, by random disruptions that infiltrate at different stages as the

image formed by the optics of the eye or of a camera is transduced into an array of intensity measurements. In order to cope both with noisy edges and with edges at different spatial scales the image must be "smoothed" by a local averaging of neighboring intensity values. The differencing operation that amounts to the taking of first and second derivatives can then be performed.

There are various ways the sequence can be managed, and much theoretical effort has gone into the search for optimal methods. In one of the simplest the two operations—smoothing and differentiation—are combined into one. In technical terms it sounds forbidding: the image is convolved with a filter that embodies a particular center-surround function, the Laplacian of a Gaussian. It is not as bad as it sounds. A two-dimensional Gaussian is the bell-shaped distribution familiar to statisticians. In this context it specifies the importance to be assigned to the neighborhood of each pixel when the image is being smoothed. As the distance increases, the importance decreases. A Laplacian is a second derivative that gives equal weight to all paths extending away from a point. The Laplacian of a Gaussian converts the bell-shaped distribution into something more like a Mexican hat. The bell is narrowed and at its sides a circular negative dip develops.

Now the procedure can be described nontechnically. Convolving an image with a filter that embodies the Laplacian of a Gaussian is equivalent to substituting for each pixel in the image a weighted average of neighboring pixels, where the weights are provided by the Laplacian of a Gaussian. Thus the filter is applied to each pixel. It assigns the greatest positive weight to that pixel and decreasing positive weights to the pixels nearby [*see illustration on next two pages*]. Then comes an annulus—a ring—in which the pixels are given negative weightings. Bright points there feed negative numbers into the averaging. The result of the overall filtering is an array of positive and negative numbers: a kind of second derivative of the image intensity at the scale of the filter. The zero-crossings in this filtered array correspond to places in the original image where its intensity changed most rapidly. Note that a binary (that is, a two-valued) map showing merely the positive and negative regions of the filtered array is essentially equivalent to a map of the zero-crossings in that one can be constructed from the other.

In the human brain most of the hardware required to perform such a filtering seems to be present. As early as 1865 Ernst Mach observed that visual perception seems to enhance spatial variations in light intensity. He postulated that the enhancement might be achieved by lateral inhibition, a brain mechanism in which the excitation of an axon, or nerve fiber, say by a spot of bright light in the visual world, blocks the excitation of neighboring axons. The operation plainly enhances the contrast between the bright spot and its surroundings. Hence it is similar to the taking of a spatial derivative.



SPATIAL DERIVATIVES of an image serve to emphasize its spatial variations in intensity. The left part of the illustration shows an edge between two even shades of gray (*a*). The intensity along a path across the edge appears below it (*b*). The first derivative of the intensity is the rate at which intensity changes (*c*). Toward the left or toward the right there is no change; the first derivative therefore is zero. Along the edge itself, however, the rate of change rises and falls. The second derivative of the intensity is the rate of change of the rate of change (*d*). Both derivatives emphasize the edge. The first derivative marks it with a peak; the second derivative marks it by crossing zero. The right part of the illustration shows an edge more typical of the visual world (*a′*). The related intensity contour (*b′*) and its first and second derivatives (*c′*, *d′*) are "noisy." The edge must be smoothed before derivatives are taken. This illustration and the one on page 108 were prepared by H. Keith Nishihara of the Artificial Intelligence Laboratory.

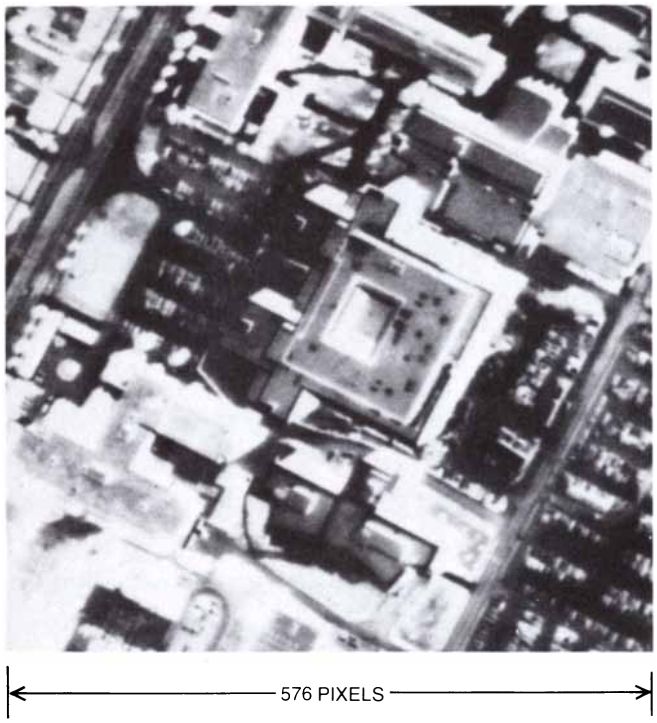
Then in the 1950's and 1960's evidence accumulated suggesting that the retina does something much like center-surround filtering. The output from each retina is conveyed to the rest of the brain by about a million nerve fibers, each being the axon of a neuron called a retinal ganglion cell. The cell derives its input (by way of intermediate neurons) from a group of photoreceptors, which form a "receptive field." What the evidence suggests is that for certain ganglion cells the receptive field has a center-surround organization closely approximating the Laplacian of a Gaussian. Brightness in the center of the receptive field excites the ganglion cell; brightness in a surrounding annulus inhibits it. In short, the receptive field has an ON-center and an OFF-surround, just like the Mexican hat.

Other ganglion cells have the opposite properties: they are OFF-center, ON-surround. If axons could signal negative numbers, these cells would be redun-

dant: they report simply the negation of what the ON-center cells report. Neurons, however, cannot readily transmit negative activity; the ones that transmit all-or-nothing activity are either active or quiescent. Nature, then, may need neuronal opposites. Positive values in an image subjected to center-surround filtering could be represented by the activity of ON-center cells; negative values could be represented by the activity of OFF-center cells. In this regard I cannot refrain from mentioning the recent finding that ON-center and OFF-center ganglion cells are segregated into two different layers, at least in the retina of the cat. The maps generated by our computer might thus depict neural activity rather literally. In the maps on the opposite page red might correspond to ON-layer activity and blue to OFF-layer activity. Zero-crossings (that is, transitions from one color to the other) would be the locations where activity switches from one layer to the other. Here, then, is a conjecture linking a computational theory of vision to the brain hardware serving biological vision.

It should be said that the center-surround filtering of an image is computationally expensive for a computer because it involves great numbers of multiplications: about a billion for an image of 1,000 pixels by 1,000. At the Artificial Intelligence Laboratory, H. Keith Nishihara and Noble G. Larson, Jr., have designed a specialized device: a convolver that performs the operation in about a second. The speed is impressive but is plodding compared with that of the retinal ganglion cells.

I should also mention the issue of spatial scale. In an image there are fine changes in intensity as well as coarse. All must be detected and represented. How can it be done? The natural solution (and the solution suggested by physiology and psychophysics) is to use center-surround filters of different sizes. The filters turn out to be band-pass: they respond optimally to a certain range of spatial frequencies. In other words, they "see" only changes in intensity from pixel to pixel that are neither too fast nor too slow. For any one spatial scale the process of finding intensity changes con-



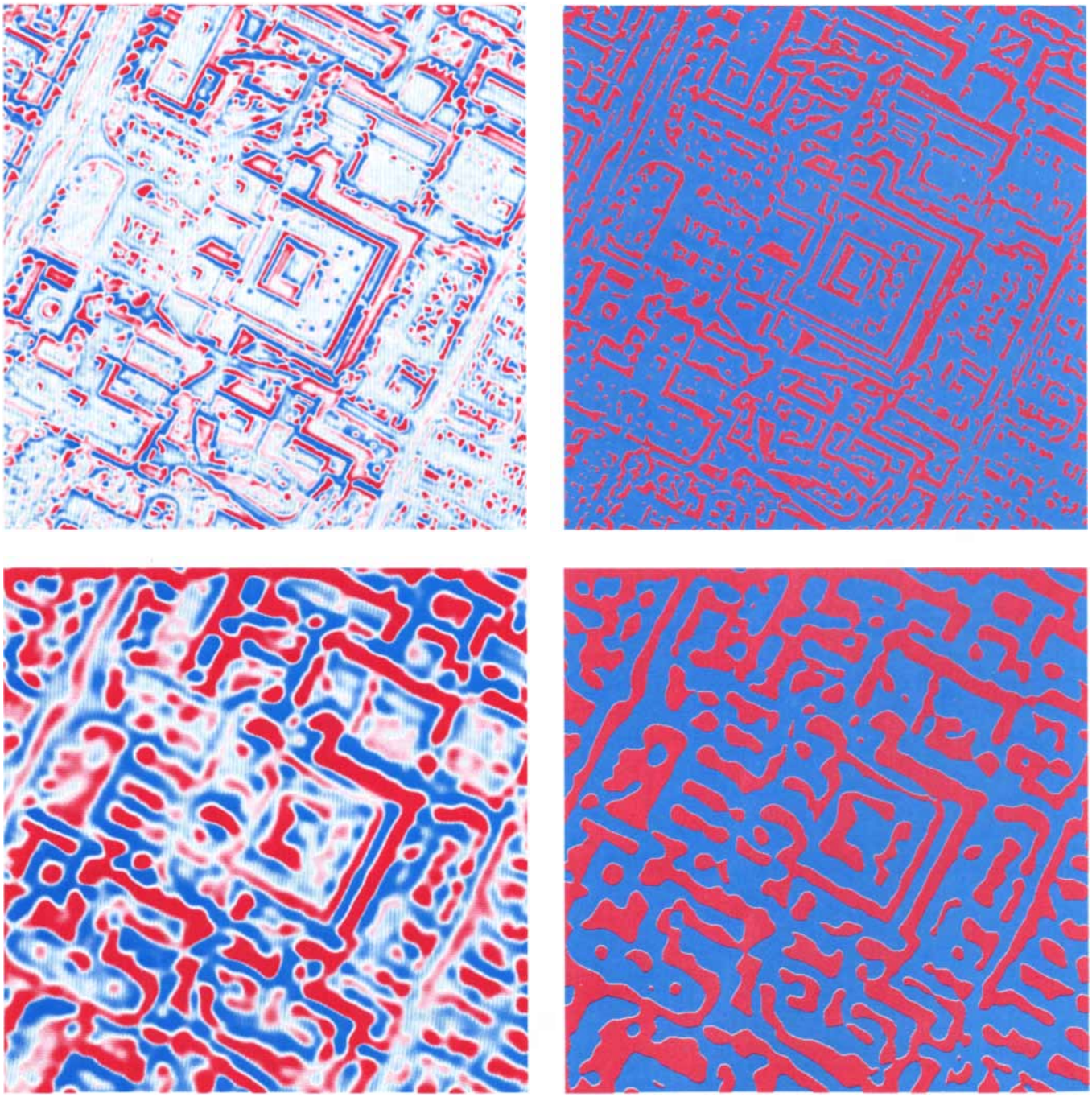
CENTER-SURROUND FILTERING of an image serves both to smooth it and to take its second spatial derivative. Here an image is shown at the left. Then filters of two sizes are shown. They are depicted schematically; the "filter" is actually computational. Specifically each intensity measurement in the image is replaced by a weighted average of neighboring measurements. Nearby measurements contribute positive weights to the average; thus the filter's center is "excitatory" (*red*). Then comes an annulus, or ring, in which the measurements contribute negative weights; thus the filter's "surround" is "inhibitory" (*blue*). The third part of the illustration shows the maps produced by the filters. They are no longer gray-level arrays. For one thing the maps have both positive values (*red*) and negative values (*blue*). They are maps of the second derivative. Transitions from one color to the other are zero-crossings; that is, they mark the places in the original image where its intensity changed most rapidly. The maps at the right of the illustration emphasize the zero-crossings by showing only positive regions (*red*) and negative regions (*blue*).

sists, therefore, of filtering the image with a center-surround filter (or receptive field) of a particular size and then finding the zero-crossings in the filtered image. For a combination of scales it is necessary to set up filters of different sizes, performing the same computation for each scale. Large filters would then detect soft or blurred edges as well as overall illumination changes; small filters would detect finer details. Sharp edges would be detected at all scales.

Recent theoretical results enhance the attractiveness of this idea by showing that features similar to zero-crossings in a filtered image can be rich in information. First, Ben Logan of Bell Laboratories has proved that a one-dimensional signal filtered through a certain class of filters can be reconstructed from its zero-crossings alone. The Laplacian of a Gaussian does not satisfy Logan's conditions exactly. Still, his work suggests that the primitive symbols provided by zero-crossings are potent visual symbols. More recently Alan Yuille and I have made a theoretical analysis of center-surround filtering. We have been able to show that zero-crossing maps obtained at different scales can represent the original image completely, that is, without any loss of information.

This is not to say that zero-crossings are the optimal coding scheme for a process such as stereopsis. Nor is it to insist that zero-crossings are the sole basis of biological vision. They are a candidate for an optimal coding scheme, and they (or something like them) may be important among the items to be matched between the two retinal images. We have, therefore, a possible answer to the question of what the stereopsis module matches. In addition we have the beginning of a computational theory that may eventually give mathematical precision to the vague concept of "edges" and connect it to known properties of biological vision, such as the prominence of "edge detector" cells discovered at the Harvard Medical School by David H. Hubel and Torsten N. Wiesel in the part of the cerebral cortex where visual data arrive.

To summarize, a combination of computational arguments and biological data suggests that an important first



step for stereopsis and other visual processes is the detection and marking of changes in intensity in an image at different spatial scales. One way to do it is to filter the image by the Laplacian of a Gaussian; the zero-crossings in the filtered array will then correspond to intensity edges in the image. Similar information is implicit in the activity of ON-center and OFF-center ganglion cells in the retina. To explicitly represent the zero-crossings (if indeed the brain does it at all) a class of edge-detector neurons in the brain (no doubt in the cerebral cortex) would have to perform specific operations on the output of ON-center and OFF-center cells that are neighbors in the retina. Here, however, one comes up against the lack of information about precisely what elementary computations nerve cells can readily do.

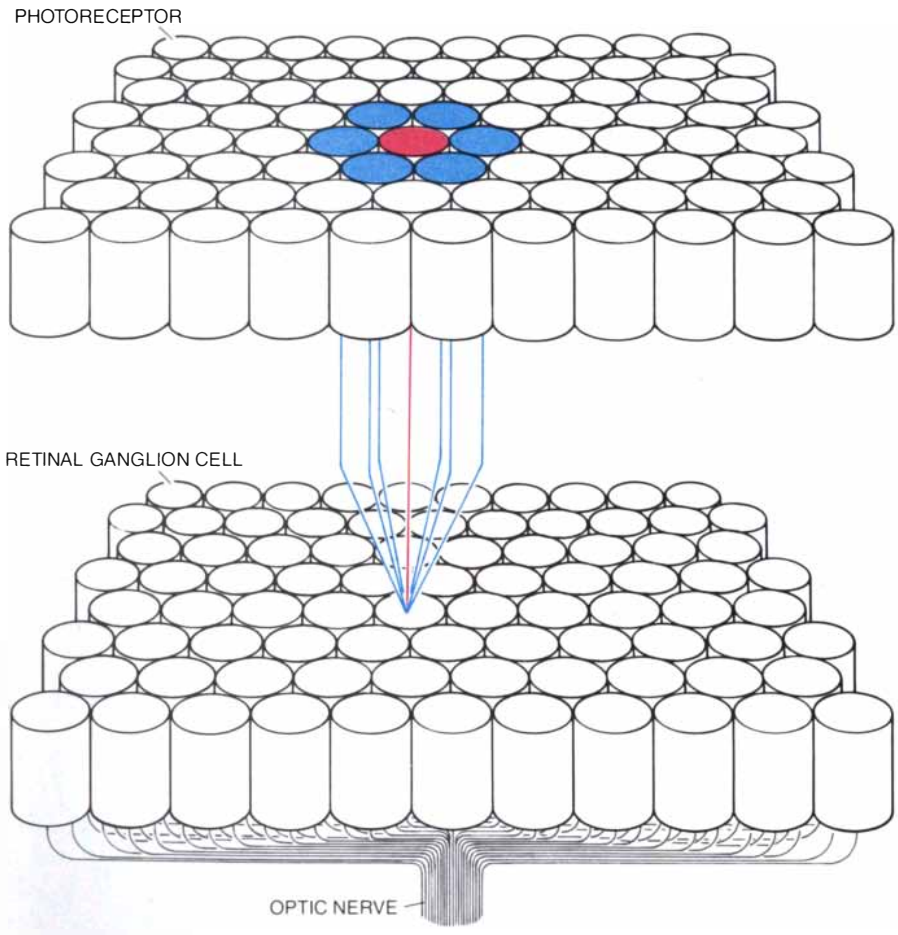
We are now in a position to see how a representation of intensity changes might be useful for stereopsis. Consider first an algorithm devised by Marr and me that implements the constraints discussed above, namely uniqueness (a given point on a physical surface has only one location, so that only one binocular match is correct) and continuity (variations in depth are generally smooth, so that binocular disparities tend to vary smoothly). It is successful at solving random-dot stereograms and at least some natural images. It is done by a computer; thus its actual execution amounts to a sequence of calculations. It can be thought of, however, as setting up a three-dimensional network of nodes, where the nodes represent all possible intersections of lines of sight from the eyes in the three-dimensional world. The uniqueness constraint will then be implemented by requiring that the nodes along a given line of sight inhibit one another. Meanwhile the continuity constraint will be implemented by requiring that each node excite its neighbors. In the case of random-dot stereograms the procedure will be relatively simple. There the matches for pixels on each horizontal row in one stereogram need be sought only along the corresponding row of the other stereogram.

The algorithm starts by assigning a value of 1 to all nodes representing a binocular match between two white pixels or two black pixels in the pair of stereograms. The other nodes are given a value of 0. The 1's thus mark all matches, true and false [*see illustration on opposite page*]. Next the algorithm performs an algebraic sum for each node. In it the neighboring nodes with a value of 1 contribute positive weights; the nodes with a value of 1 along lines of sight contribute negative weights. If the result exceeds some threshold value, the node is given the value of 1; otherwise the node is set to 0. That constitutes one iteration of the procedure. After a few such iterations the network reaches stability. The stereopsis problem is solved.

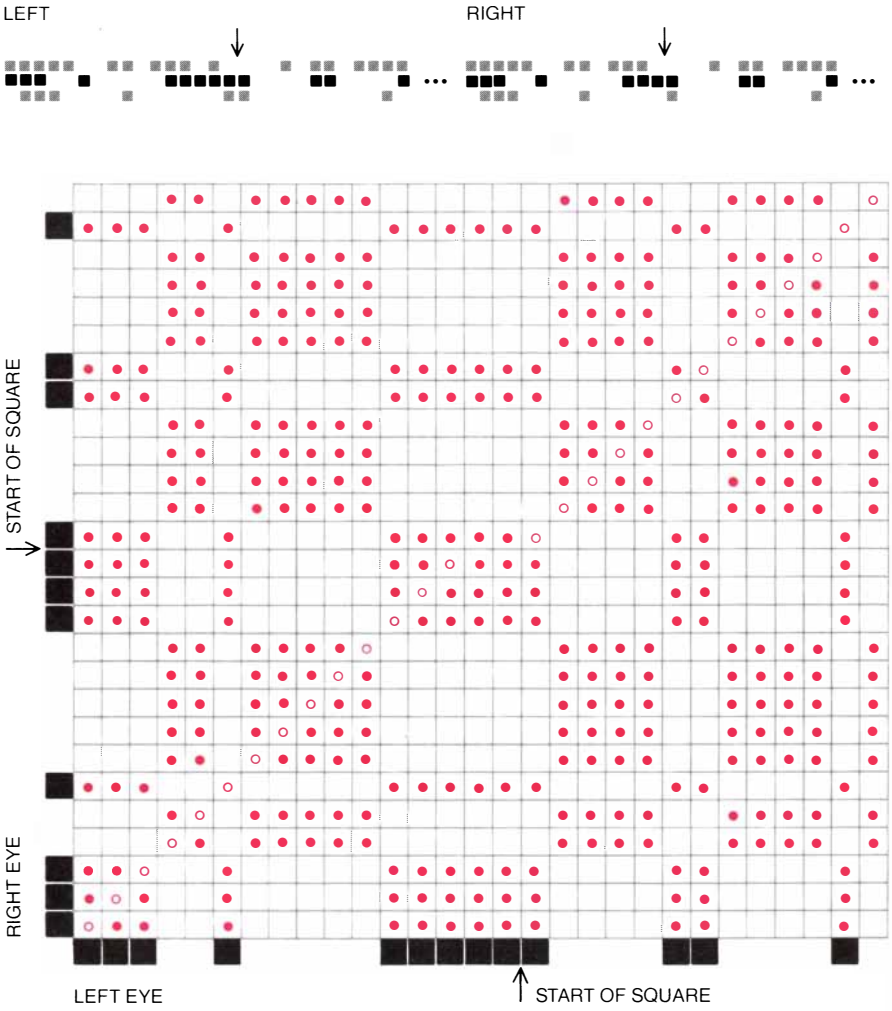
The algorithm has some great virtues. It is a cooperative algorithm: it consists of local calculations that a large number of simple processors could perform asynchronously and in parallel. One imagines that neurons could do them. In addition the algorithm can fill in gaps in the data. That is, it interpolates continuous surfaces. At the same time it allows for sharp discontinuities. On the other hand, the network it would require to process finely detailed natural images would have to be quite large, and most of the nodes in the network would be idle at any one time. Furthermore, intensity values are unsatisfactory for images more natural than random-dot stereograms.

The algorithm's effectiveness can be extended to at least some natural images by first filtering the images to obtain the sign of their convolution with the Laplacian of a Gaussian. The resulting binary maps then serve as inputs for the cooperative algorithm. The maps themselves are intriguing. In the ones generated by large filters at correspondingly low spatial resolution, zero-crossings of a given sign (for instance the crossings at which the sign of the convolution changes from positive to negative) turn out to be quite rare and are never close to each other. Thus false targets (matches between noncorresponding zero-crossings in a pair of stereograms) are essentially absent over a large range of disparities.

This suggests a different class of stereopsis algorithms. One such algorithm, developed recently for robots by Nishihara, matches positive or negative patches in filtered image pairs. Another algorithm, developed earlier by Marr and me, matches zero-crossings of the same sign in image pairs made by filters of three or more sizes. First the coarsely filtered images are matched and the binocular disparities are measured. The results are employed to approximately register the images. (Monocular features such as textures could also be used.) A similar matching process is then applied to the medium-filtered images. Finally the process is ap-



BIOLOGICAL FILTER embodied by cells in the retina resembles in its effect the computer procedure shown in the illustration on the preceding two pages. The filter begins with a layer of photoreceptors, which measure the light intensity of the visual world. They are connected by way of intermediate nerve cells not shown in the diagram to a layer of retinal ganglion cells, which send visual data to higher visual centers of the brain. For the sake of simplicity only one set of connections is shown. A photoreceptor cell (*red*) excites an "ON center" ganglion cell by promoting its tendency to generate neural signals; the surrounding photoreceptors (*blue*) inhibit the ganglion cell. The arrangement amounts to biological center-surround filtering.



STEREOPSIS ALGORITHM devised by Marr and the author reconstructs the three-dimensional visual world by seeking matches between dots on corresponding rows of a pair of random-dot stereograms. At the top of the illustration two such rows are shown (*black and white*). Below them the rows are placed along the axes of a chart. Horizontal lines across the chart then represent lines of sight for the right eye; vertical lines represent lines of sight for the left eye. Color marks all intersections at which the eyes both see a black dot or a white dot. The problem is plain. A given black dot in one stereogram could in principle match any black dot in the other. The same is true for the white dots. Yet only some matches are correct (*open colored circles*), that is, only some matches reveal that a square of random-dot texture has a binocular disparity. The explanation of the algorithm continues in the illustration on the next page.

plied to the most finely filtered images. By that time the binocular disparities in the stereo pair are known in detail, and so the problem of stereopsis has been reduced to trigonometry.

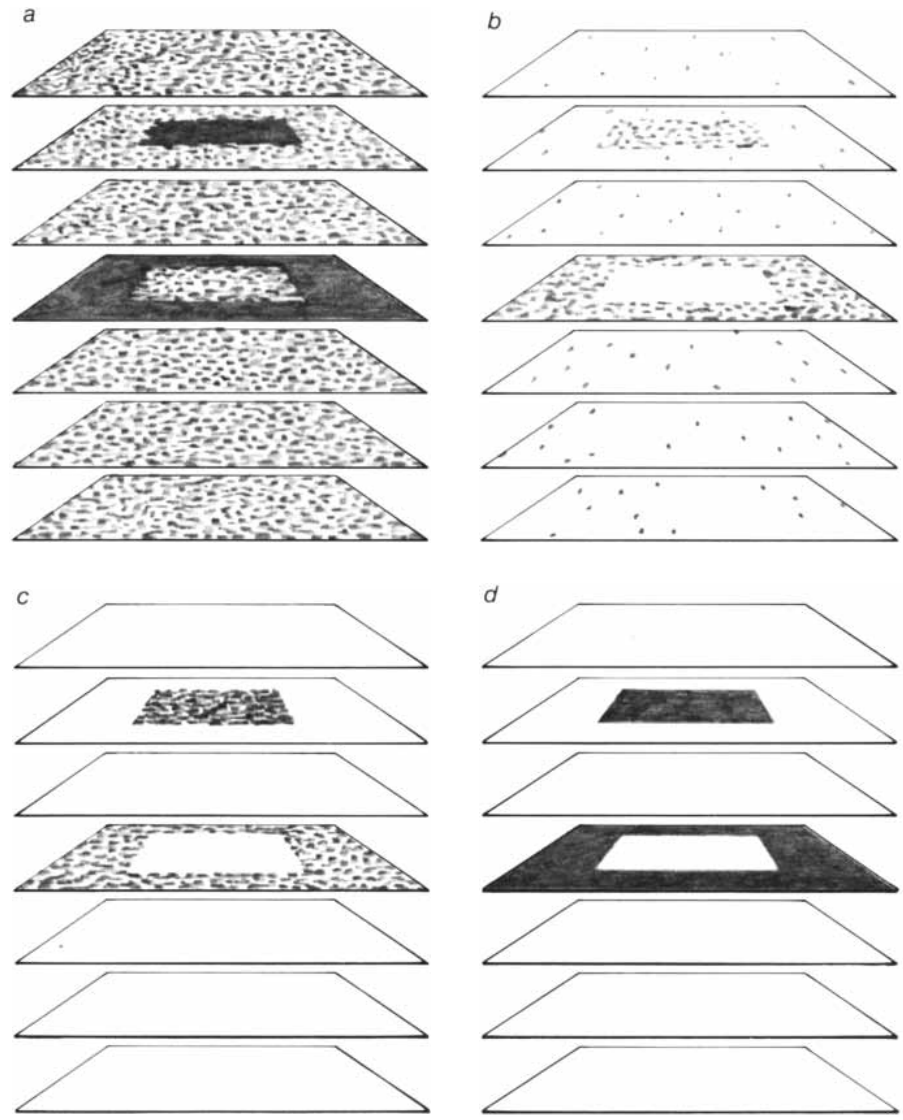
A theoretical extension and computer implementation of our algorithm by W. Eric L. Grimson at the Artificial Intelligence Laboratory works quite well for a typical application of stereo systems: the analysis of aerial photographs. In addition it mimics many of the properties of human depth perception. For example, it performs successfully when one of the stereo images is out of focus. Yet there may also be subtle differences. Recent work by John Mayhew and John P. Frisby at the University of Sheffield and by Julesz at Bell Laboratories should clarify the matter.

What can one say about biological stereopsis? The algorithms I have described are still far from solving the correspondence problem as effectively as our own brain can. Yet they do suggest how the problem is solved. Meanwhile investigations of the cerebral cortex of the cat and of the cerebral cortex of the macaque monkey have shown that certain cortical neurons signal binocular disparities. And quite recently Gian F. Poggio of the Johns Hopkins University School of Medicine has found cortical neurons that signal the correct binocular disparity in random-dot stereograms in which there are many false matches. His discovery, together with our computational analysis of stereopsis, promises to yield insight into the brain mechanisms underlying depth perception.

One message should emerge clearly: the extent to which the computer and

the brain can be brought together for the study of problems such as vision. On the one hand the computer provides a powerful tool for testing computational theories and algorithms. In the process it guides the design of neurophysiological experiments: it suggests what one should look for in the brain. The impetus this will give brain research in the coming decades is likely to be great.

The benefit is not entirely in that direction; computer science also stands to gain. Some computer scientists have maintained that the brain provides only existence proofs, that is, a living demonstration that a given problem has a solution. They are mistaken. The brain can do more: it can show how to seek solutions. The brain is an information processor that has evolved over many millions of years to perform certain tasks superlatively well. If we regard it, with justified modesty, as an uncertain instrument, the reason is simply that we tend to be most conscious of the things it does least well—the recent things in evolutionary history, such as logic, mathematics and philosophy—and that we tend to be quite unconscious of its true powers, say in vision. It is in the latter domains that we have much to learn from the brain, and it is in these domains that we should judge our achievements in computer science and in robots. We may then begin to see what vast potential lies ahead.



ITERATIONS OF THE ALGORITHM (depicted schematically) solve the problem of stereopsis. The algorithm assigns a value of 1 to all intersections of lines of sight marked by a match. The others are given a value of 0. Next the algorithm calculates a weighted sum for every intersection. Surfaces in the three-dimensional world tend to vary smoothly in depth; hence neighboring intersections with a value of 1 contribute positive weights to the sum. The eye sees only one surface along a given line of sight; hence intersections with a value of 1 along lines of sight contribute negative weights. If the result exceeds a threshold value, the intersection is reset to 1; otherwise it is reset to 0. After a few iterations of the procedure the calculation is complete: the stereograms are decoded. Natural images transformed into binary arrays (that is, into two-value zero-crossing maps) after center-surround filtering can be processed similarly.

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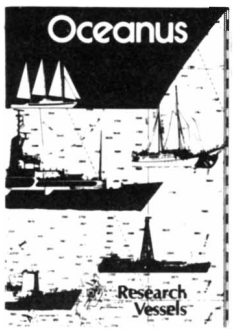

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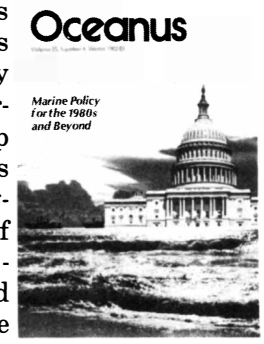

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Cell-Adhesion Molecules: A Molecular Basis for Animal Form

Molecules mediating cell-to-cell adhesion appear dynamically during development. They may regulate cell movements and tissue placements that govern both the shape of the embryo and the formation of organs

by Gerald M. Edelman

The organized growth of an embryo from a single fertilized egg to a functioning adult has fascinated biologists from ancient times to the present. Although the successive events of embryonic development in many species have been described in precise detail, the fundamental question of embryology still challenges the most sophisticated resources of modern biology: What controls the process of morphogenesis, or the origin of form? In other words, how does a one-dimensional genetic code ultimately specify a three-dimensional organism?

The question must be answerable at the molecular level, but it is not likely to be answered by the straightforward application of the methods of molecular biology alone. The primary processes of development—cell division, cell movement, cell adhesion, cell differentiation and cell death—defy analysis in terms of lists of genes and linear interactions of their protein products. Each of these processes is the result of myriads of molecular events, which are regulated in parallel not only by interacting genes but also by concomitant epigenetic events: those not specified directly by particular genes. Given the microscopic nature of all these events and their remarkable complexity it is perhaps no wonder that there is as yet no adequate theory of development in the same sense that there are adequate theories of genetics and evolution. Constructing such a theory is a particularly compelling challenge because the determination of the nature and regulation of genetic and epigenetic sequences in embryonic development and their relation to evolution is perhaps the grandest outstanding puzzle in biology.

One approach to solving part of the puzzle is to choose a single primary process, to attempt to analyze it at the molecular level and then to relate the analysis to the other primary processes crucial for morphogenesis. Which of the developmental processes should one choose? The choice depends to some extent on whether one is interested mainly in the differentiation of individual cells or in pattern formation. A strategy adopted in our laboratory at Rockefeller University, where the major interest is in pattern formation, is to focus sharply on the primary process whereby cells adhere to one another. Cell adhesion must take place at every stage of development to establish form, and it is the process most susceptible to direct chemical assault. Moreover, it is the process most obviously related to the maintenance of final form. The analysis of adhesion is particularly attractive because adhesion is mediated by protein molecules. The proteins are directly specified by the genetic code, and therefore both their function in determining embryonic form and the control of their genes can be related within one system. Although the determination of embryonic form will be fully understood only when all the primary processes are analyzed, work done on cell adhesion over the past decade provides an encouraging beginning because it prompts fruitful hypotheses suggesting how certain aspects of the puzzle of morphogenesis may eventually be resolved.

To indicate the nature of the problem let me briefly review some major early events in the development of the chick embryo. Shortly after fertilization a succession of cell divisions results in the formation of the blastoderm, a flat disk on the egg membrane above the yolk. The topmost cells of the blastoderm constitute the epiblast, which gives rise to an underlying sheet called the hypoblast and later to a middle layer, the mesoblast. The fundamental event in early morphogenesis is the formation from these precursor cells of the embryo's three germ layers: the ectoderm, the mesoderm and the endoderm. In this process, called gastrulation, patterned cell movements and alterations of sheets of tissue follow one another in precise succession. The epiblast itself gives rise to the ectoderm and, along with parts of the hypoblast, to the endoderm; the mesoblast gives rise to the mesoderm. In later stages the ectoderm, the outermost layer of the embryo, develops to form the nervous system and the skin. The endoderm gives rise to the lungs, the intestines and other organs. The mesoderm ultimately gives rise to muscles, kidneys and bones.

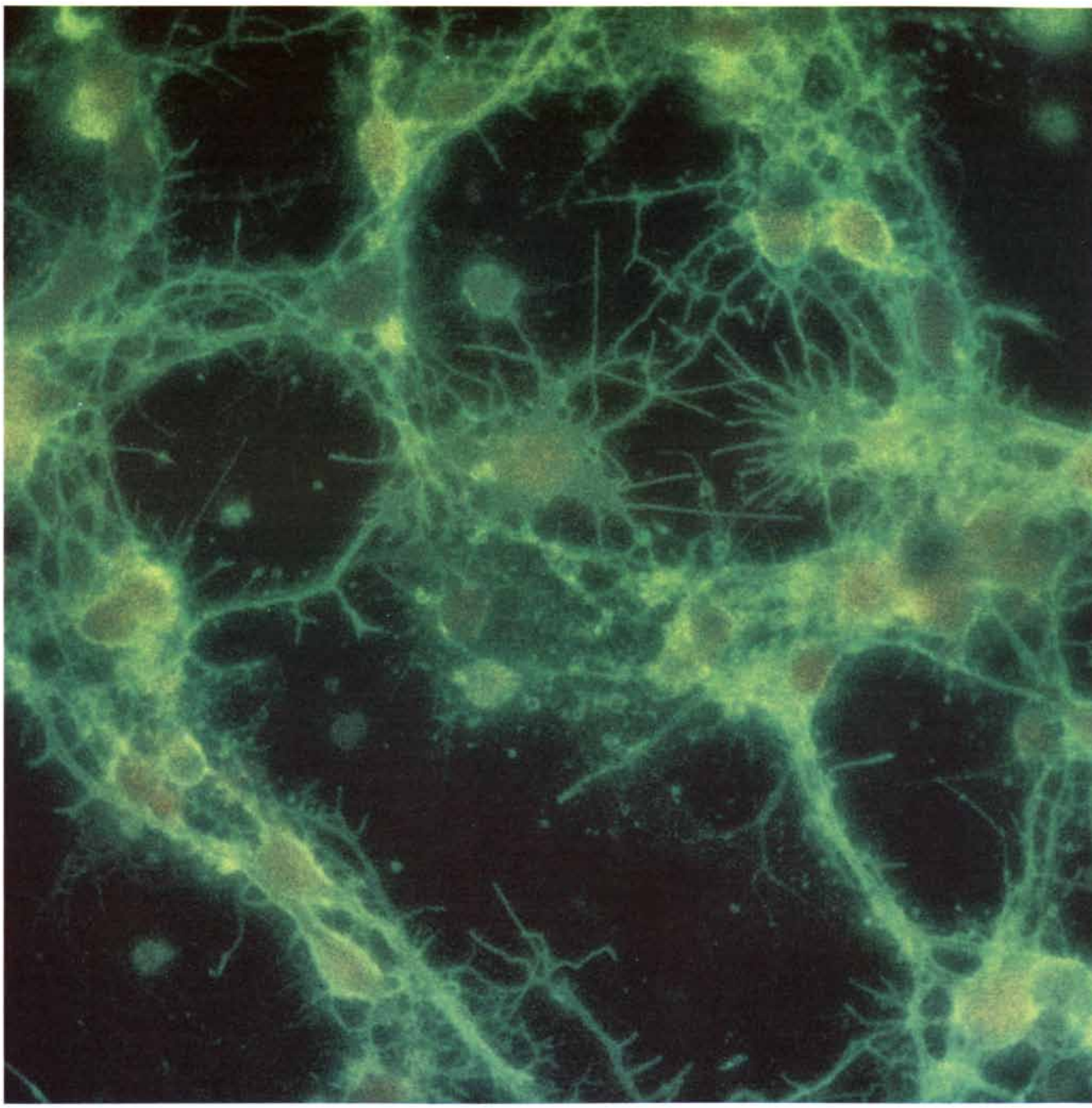
The process of key significance to all further events is embryonic induction, in which cells differentiating to give rise to structures in one layer require the presence of cells with a different history (from either the same layer or a different one); the apposition of cells is ordinarily achieved by morphogenetic movements. Induction, or milieu-dependent differentiation, begins with gastrulation. In the embryo it is the result of continuing sequences of reciprocal interactions between different groups of cells and is brought about either by direct cellular contact or by the transfer of molecular factors. Among the earliest and most critical of all such inductions is the one that causes ectodermal cells to become the precursors of neural tissues such as the brain and the spinal cord. This primary, or neural, induction depends on interactions of the mesoderm and the ectoderm and results in the formation of the neural plate from the ectoderm. Later the neural plate undergoes a coordinated set of foldings (neurulation) to form the neural tube. Different parts of the underlying mesoderm have different effects in determining the forebrain, the midbrain and hindbrain, and the spinal cord. Induction is regionally specialized because it is the result of a sequence, in time and in space within the changing embryo, of stimulatory or inhibitory signals.

Early in embryogenesis some morphogenetic events reflecting the vari-

ous primary processes can actually be seen: the sweeping of endodermal cells toward the interior of the blastoderm during gastrulation through the groove called the primitive streak; the segregation of mesodermal cells to form somites, which are segmented precursors of muscular and skeletal structures; the grouping of elongating ectodermal cells to yield the structures known as placodes, which eventually give rise to such specialized derivatives as nerve ganglia and the lens of the eye. Complex endodermal organs such as the liver and the pancreas form from the early gut endoderm. Mesodermal organs such as the kidney, with its complex tubular structures, are formed after a series of reciprocal inductions. A process that is particularly important for the appropriate tissue appositions and inductions is the conversion of sheets of attached cells (epithelia) into moving masses of loosely organized cells (mesenchyme); the reverse process is equally important in certain embryonic regions.

Development is historical. Not only primary induction but also the entire series of secondary inductions yielding the organs mentioned above depend on the apposition of particular cells that have had different histories. This extraordinary series of events takes place in a well-defined temporal sequence and is organized in stages, with structures in each stage serving as the basis of structures in succeeding stages.

How can the classical descriptions of morphogenesis be translated into the language of molecules? As I have indicated, our strategy has been to look for molecules mediating cell adhesion, to



N-CAM, a cell-adhesion molecule associated with neural tissue, is shown to be present on the cell bodies and the elongating processes of cultured chick-embryo neurons, which are enlarged some 1,200 diameters in a fluorescence micrograph made by Cheng-Ming Chuong in the author's laboratory. The cells were treated with an antibody to N-CAM labeled with the fluorescent dye fluorescein, which gives off a green glow under ultraviolet illumination. The antibody has bound to CAM's on all cell surfaces, including the growth cones: spatulate motile structures, at the ends of growing neuronal processes, a number of which are seen clearly at the center of the micrograph.

study their structure and how they work and then to relate our findings to key events and sequences in other primary processes of development. Before describing the experimental results I shall explore some general ideas relating adhesion to pattern, because pattern formation is the central issue in developmental biology.

There are two alternative ways patterns might be formed at the cellular level without the direct intervention of some kind of "little architect" or "construction demon." The first way would require prelabeling all cells with molecular markers (presumably proteins), each one spatially complementary to some other marker on a cell to be placed next to it in the pattern. This is essentially how parts of the great offshore abbey of Mont-Saint-Michel were built. Stones were cut and shaped on the mainland, marked by their makers and reassembled on the island according to a plan. This Mont-Saint-Michel model is a metaphor for various "chemoaffinity" theories of cell adhesion. The major difficulty with such theories is that if the pattern to be formed is complex, has much variation in shape or has many elements and much local detail (as, for example, in the brain), then the number of specific surface markers determining each cell's location must be enormous. Inasmuch as such markers are most likely to be specific proteins, each encoded by a different gene, the number of genes would be correspondingly large. As would be the case for a misnumbered keystone of an arch, a misplaced cellular marker could cause havoc. Moreover, a pattern made this way is prefigured and essentially static: once the right markers come together, no further dynamism is necessary.

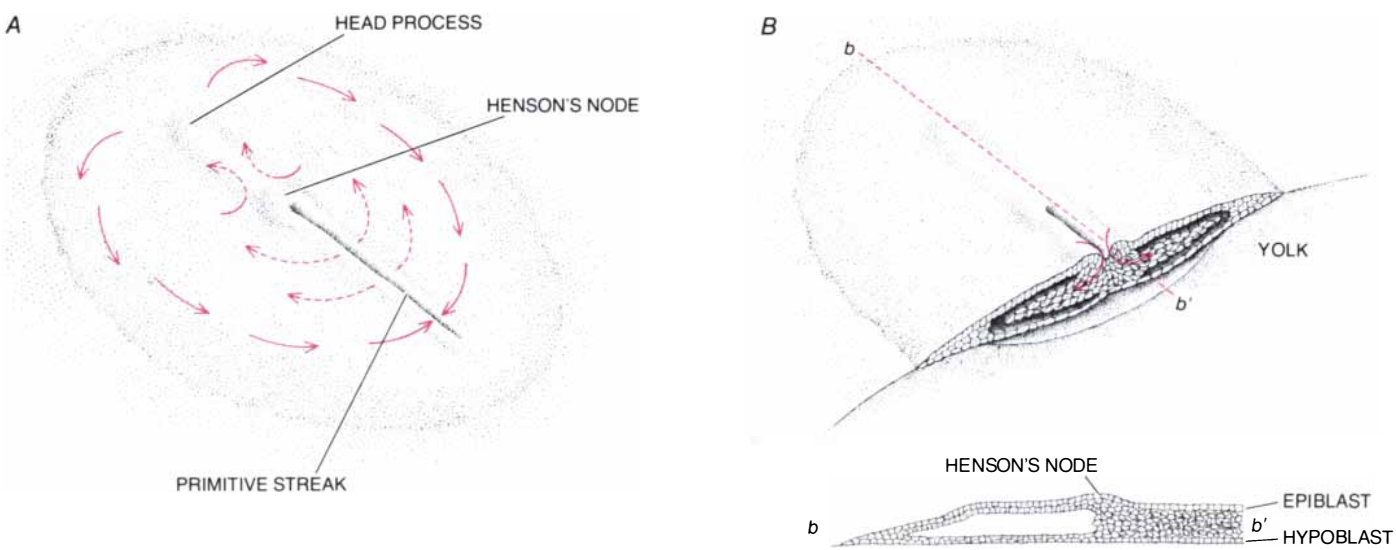
There is an alternative and more dynamic way of generating patterns, akin to what might be observed in a mountain stream. In this kinetic, far-from-equilibrium situation, pattern results from the play of energy as it is dissipated into the environment against various constraints. To make the simplest case for this mountain-stream model, imagine a stream of water running down a mountainside and striking a submerged boulder whose temperature is below freezing. At first the flow of water will be influenced only slightly by the boulder and the stream will remain a single stream. In time, however, as water freezes onto the boulder, the enlarging structure may suddenly become a barrier causing the stream to split in two and assume a new shape as it runs down the mountain. All subsequent shapings of the stream will be influenced by the effect of the original freezing. Rivulets downstream may break into a variety of new and intricate patterns as they meet different constraints at lower levels. Seen from above, the entire stream will nonetheless have a definite shape.

In an embryo, of course, things are more complicated. Still, one can imagine that the cellular counterparts to the driving force of the gravitational potential on the mountain might be the processes of cell division, cell death and cell movement. The counterpart to the freezing of the water would be the attachment of cells to one another by cell-adhesion molecules (CAM's) that are displayed on the cell surface; complete freezing would correspond to such tight binding that certain cells could no longer move with respect to one another. The important thing to note is that in order to obtain a given number of cellular patterns in a process analogous to the mountain-stream model, the number of different specific CAM's need not be nearly as large as the number of postulated recognition markers in the Mont-Saint-Michel model, provided only that there is some dynamic way to change how strongly the CAM's are bound to one another. Almost certainly one CAM will not be enough; even given the dynamic range of the kinetic model, some molecules with new specificities may be needed to generate certain patterns.

This discussion should make clear the necessity for distinguishing between cell adhesion and cell recognition. If cell proximity is involved, recognition by prefigured markers clearly implies local specificity (as in the Mont-Saint-Michel model), but if adhesion is subject to dynamic changes, it need not in itself require such a degree of recognition. Pattern can arise without individual cell-to-cell recognition, and one must therefore distinguish between specificity of recognition and the selectivity (or fixation of pattern) that can emerge from the interaction of diverse dynamic processes.

Yet another distinction needs to be made. The names of the different cells that are bound together should not be confused with the names of the different molecules that mediate their binding. By convention we call the binding of similar cells homotypic and the binding of similar molecules homophilic. The distinction is not trivial. It is possible to have heterotypic binding (between different kinds of cell) by a homophilic mechanism (one mediated by similar molecules).

My colleagues and I began our search for CAM's with the assumption that they must be molecules on the cell surface, were likely to be proteins and were also likely to be scarce. One way to



KEY MORPHOGENETIC EVENTS in the early development of the chick embryo are gastrulation (*A, B*) and neurulation (*C, D*). In late gastrulation cells from the top layer of the blastoderm converge toward the central groove (*solid arrows*) called the primitive streak; movements of the mesoblast (middle layer) cells are shown by broken arrows (*A*). A cross section (*B*) shows these cells spreading out to

find a scarce protein having a defined activity is to develop specific antibodies capable of inhibiting the protein's activity. The purified antigen binding to such antibodies is likely to be the desired protein. At every step in the purification process one needs assays that measure the extent to which the activity (cell adhesion in the case of the putative CAM's) is enriched as the protein is purified. We developed two kinds of assays: detection assays that would reveal the presence of CAM's and measure their activity, and perturbation assays that would reveal the ability of specific antibodies against putative CAM's to interfere with the cell adhesion the CAM's mediate and so to disrupt tissue patterns.

For detection assays we dissociated the cells of a tissue by digesting it with the enzyme trypsin, which cleaved protein molecules on the cell surface. After a recovery time during which the isolated cells could resynthesize their surface proteins, the cells were allowed to collide and adhere to one another.

To detect the specific molecules responsible for the binding of cell surfaces we took a cue from Günther Gerisch of the Max Planck Institute for Biochemistry, who exploited antibodies to perturb adhesion in slime molds: we looked for antibodies to CAM's that would specifically block adhesion. Rabbits were immunized with chick brain and retinal tissue, and the resulting antibodies were scanned for their ability to block adhesion. (The *Y*-shaped antibodies were first cleaved to make "univalent" fragments, called *Fab'* fragments, each of which had only one site that could bind to a particular antigen molecule. Uncleaved antibodies are divalent and instead of blocking adhesion would actually have bound two cells together by their CAM's.) After a year of laborious search our detection assays revealed the presence of specific adhesion-blocking antibodies. These inhibitory antibodies were, however, mixed in the rabbit serums with other antibodies directed not against a CAM but against other cell-surface molecules; because of their heterogeneity they could not serve as specific probes to identify CAM's or to isolate them.

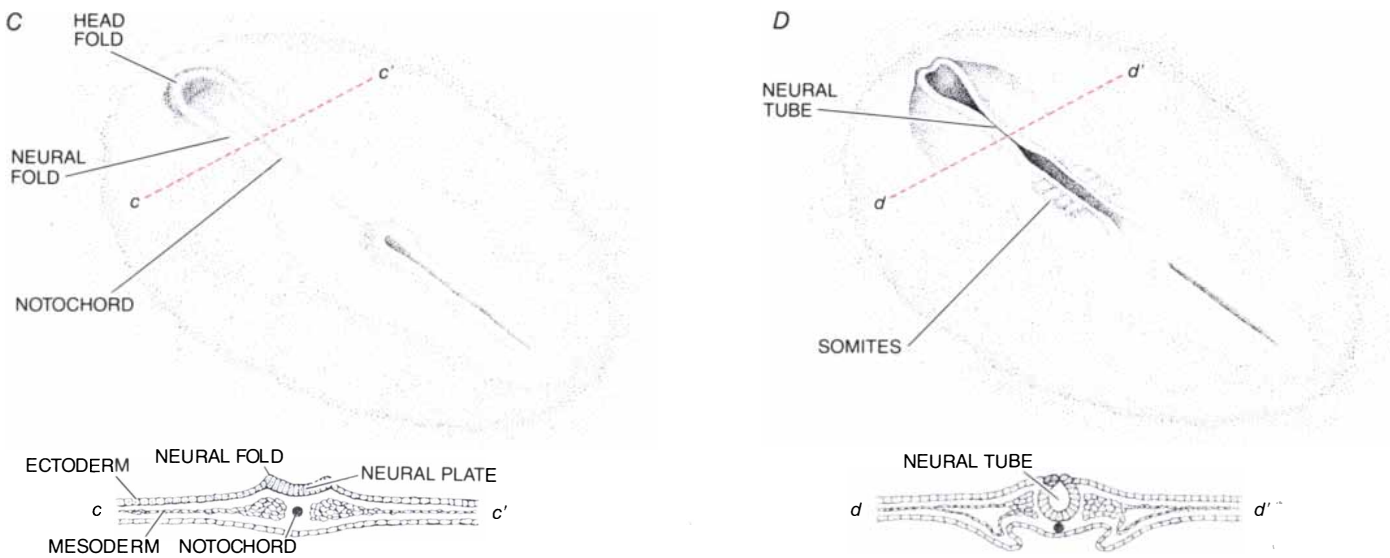
We therefore devised a "neutralization" assay to reduce the heterogeneity of the antibody population. Successive fractions of surface antigens were tested for their ability to bind to the antibodies responsible for inhibition and thus neutralize their inhibitory action. Rabbits were then reimmunized with the neutralizing surface-antigen fractions, which were relatively enriched in CAM's. Iteration of this procedure generated antigenic fractions that were pure enough to elicit highly specific anti-CAM antibodies in the rabbits and even more specific monoclonal antibodies in mice. Once the nature of CAM antigens was known we could make antibodies to CAM's from a number of animal species.

With such a variety of antibodies in hand we could check the distribution of CAM's in different tissues and also attempt specifically to disrupt the development of tissue patterns. For example, by labeling the antibodies (elicited with antigens from brain and retina) with a fluorescent marker we were soon able to show that a particular neural cell-adhesion molecule, which we designated N-CAM, is present on all neurons in the central and peripheral nervous systems. Antibodies to N-CAM disrupted the orderly development of neural tissues, such as those of the retina, as they grew in tissue culture. Similar techniques led to the identification of two other adhesion molecules: L-CAM, originally isolated intact from embryonic liver cells by Bruce A. Cunningham and Warren J. Gallin, and Ng-CAM (for neuron-glia), isolated from neurons by Martin Grumet and me.

By means of classical chromatographic fractionation and affinity chromatography (which depends on the specificity of antibodies to CAM's) we were able to purify N-CAM and L-CAM to the point where Cunningham and his associates could begin to analyze their structure. Both molecules are glycoproteins, that is, proteins to which groups of sugar molecules are attached. N-CAM is unusual in that it contains extraordinarily large amounts of a complex negatively charged sugar called sialic acid in an unusual polymerized form.

Once the adhesion molecules were purified we could cleave them with enzymes to construct linear maps of N-CAM and L-CAM. The maps indicated that the molecules are structurally different. The protein chain of N-CAM (which, exclusive of sugar, has a maximum molecular weight of 160,000) consists of three domains linked by two stretches of chain that are particularly susceptible to enzymatic cleavage. The amino-terminal domain projects away from the cell and incorporates a region that binds to a corresponding region of N-CAM on another cell. A middle domain carries the great bulk of the sialic acid. The carboxyl-terminal domain is associated with the cell membrane, and part of it appears to be inserted into the bilayer of lipid molecules constituting the membrane.

We found that the complete N-CAM chain could readily be associated with

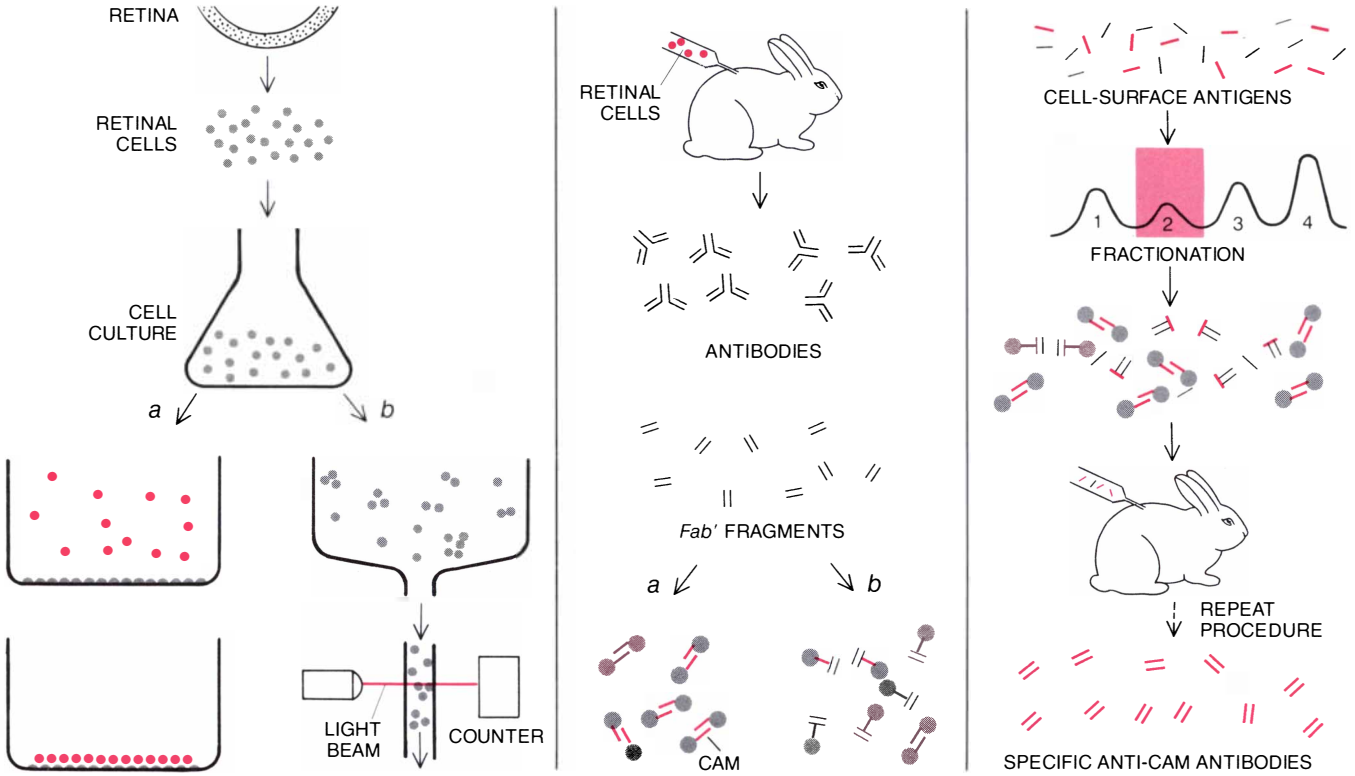


form what will become the mesoblast and ultimately the mesoderm. The sagittal section (*b*—*b'*) is alongside the primitive streak. In primary (neural) induction, a key event, interactions between mesoderm and endoderm result in the formation of the neural plate (*C*). The plate folds to form the neural tube; soon afterward mesodermal cells segregate to form the segmented precursors called somites (*D*).

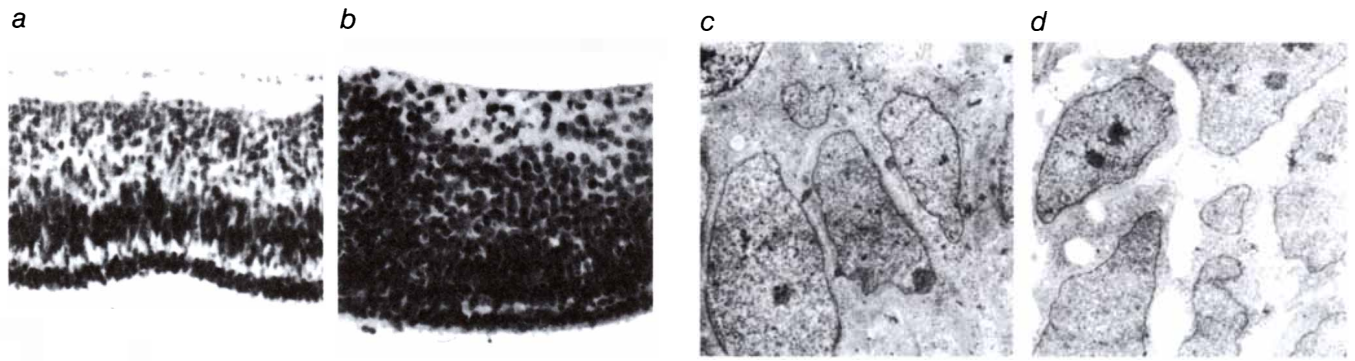
artificial lipid vesicles to make a convenient experimental system for studying the binding behavior of the molecule. For example, vesicles carrying N-CAM bind to neural cells, but if the cells are first treated with anti-N-CAM antibody fragments, the vesicles fail to bind. This supported our initial surmise that the adhesion mechanism is homophilic: that N-CAM on one cell binds to N-CAM on another cell.

The suggestion that there may be domains in N-CAM has recently received support from preliminary electron-microscope studies done in collaboration with Carolyn Cohen of Brandeis University. When N-CAM is mounted on a grid and shadowed with metal, some of the molecules (but not all of them) display a remarkable tripartite structure called a triskelion. Presumably each of the three arms of this structure corresponds to one N-CAM protein chain. Each arm is bent into regions that may correspond to individual domains. Further studies done with N-CAM in membranes may reveal other forms of the molecule and show whether any of the conformations of N-CAM in the living cell resemble those seen on the electron-microscope grid.

We wondered whether N-CAM's unusual sialic acid content plays a role in



CAM'S ARE ISOLATED by these procedures devised by the author with Robert Brackenbury, Urs Rutishauser and Jean-Paul Thiery. Adhesion assays (*left*) test CAM activity at each stage. Chick retinal cells are dissociated and allowed to resynthesize their surface molecules. Their adhesion is tested either by counting the labeled cells that bind to a fixed layer of cells (*a*) or by shaking cells together and measuring the extent to which they aggregate (*b*). In an inhibition assay (*middle*) rabbits immunized with chick retinal cells make antibodies to cell-surface proteins. The antibodies are cleaved to make univalent *Fab'* fragments. Whereas chick retinal cells ordinarily adhere to each other (*a*), anti-CAM antibody fragments inhibit such adhesion by binding to the CAM's (*color*) that mediate adhesion (*b*). A neutralization assay (*right*) is needed to identify specific anti-CAM antibodies. Surface antigens (including CAM's) from retinal cells are fractionated and the various fractions are tested for their ability to bind to the antibodies responsible for inhibition and thus to neutralize the inhibition. A fraction (*color*) that neutralizes effectively is thereby identified as being rich in CAM's, and so the blood serum of rabbits immunized with such a fraction is enriched in anti-CAM antibodies. Iteration of the procedure generates highly specific anti-CAM antibodies.

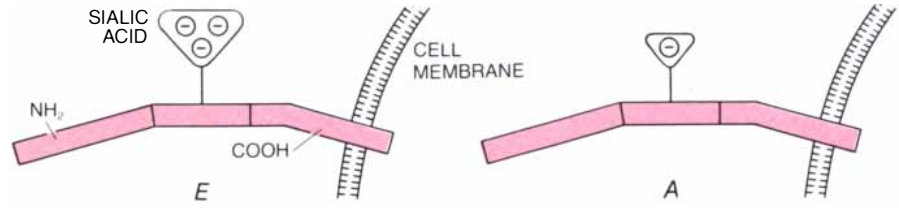


ANTIBODY TO N-CAM perturbs the orderly growth of embryonic neural tissue. Retinas were removed from six-day chick embryos and were cultured for three days with normal rabbit antibodies (univalent *Fab'* fragments) as a control (*a, c*) and with highly specific anti-N-CAM antibody (*b, d*). The photomicrographs show that the normal layered structure of the retina (*a*) is disrupted by the anti-N-CAM antibody (*b*). The electron micrographs, showing cells from the same tissues, contrast the close apposition of cell membranes in the normal sample (*c*) with the lesser extent of cell-to-cell contact and the large areas of extracellular space in the disrupted retinal tissue (*d*).

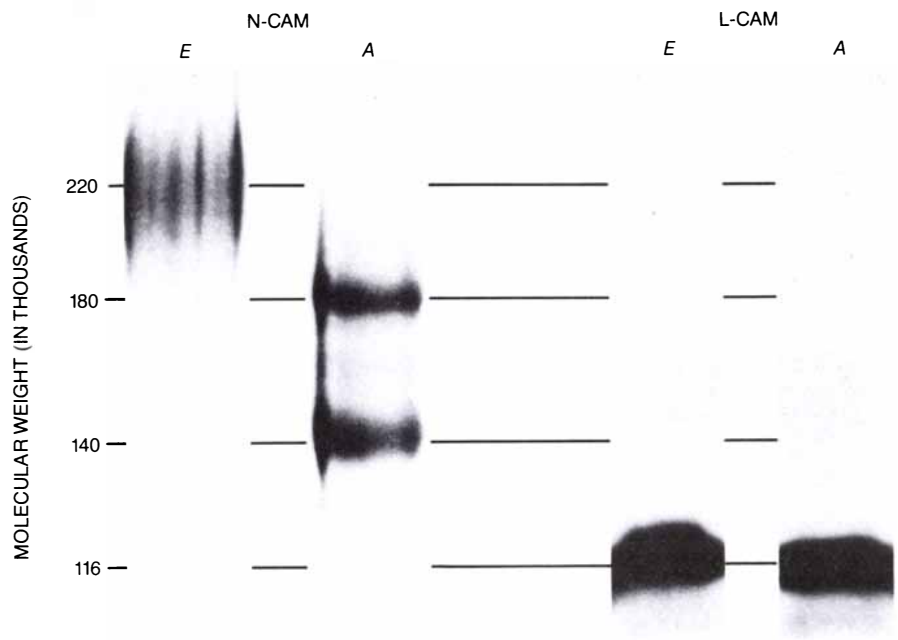
cell-to-cell binding. The answer turned out to be that it does not have a direct role: N-CAM molecules from which all the sialic acid has been removed by the enzyme sialidase will still bind specifically to cells. This finding did not, however, rule out an indirect role for sialic acid in the binding. Indeed, two observations have shown an unexpected but very important function for this sugar. The first observation was that there are two main forms of the N-CAM molecule. N-CAM from embryonic brain has 30 grams of sialic acid for every 100 grams of protein. It migrates, when it is subjected to electrophoresis, as a diffuse band with a molecular weight ranging from 200,000 to 250,000. In contrast, N-CAM from adult brain has only 10 grams of sialic acid per 100 grams of protein and forms two or three sharp bands on the electrophoretic gel. At some time during development the embryonic (*E*) form of the molecule must be converted into, or be exchanged for, one of several adult (*A*) forms. The second salient observation was that the *A* forms appear to bind more effectively than the *E* form does. As will emerge below, major changes in the relative amounts of the *E* form and the *A* forms in different parts of the developing nervous system are interpretable in the light of this difference in binding.

The detailed structures of the other two identified cell-adhesion molecules are less well worked out, but the molecules are clearly different from each other and from N-CAM. L-CAM has a molecular weight of 124,000, less than that of N-CAM, and it lacks the unusual polysialic acid. Unlike N-CAM, L-CAM mediates cell adhesion only when calcium ions are present. It is not definitely known whether L-CAM binding is homophilic. Structural and cleavage studies of L-CAM indicate that the protein part of the molecule also differs considerably from that of N-CAM. Although L-CAM was first isolated from liver cells, it plays a fundamental role in conjunction with N-CAM during the early development of the embryo.

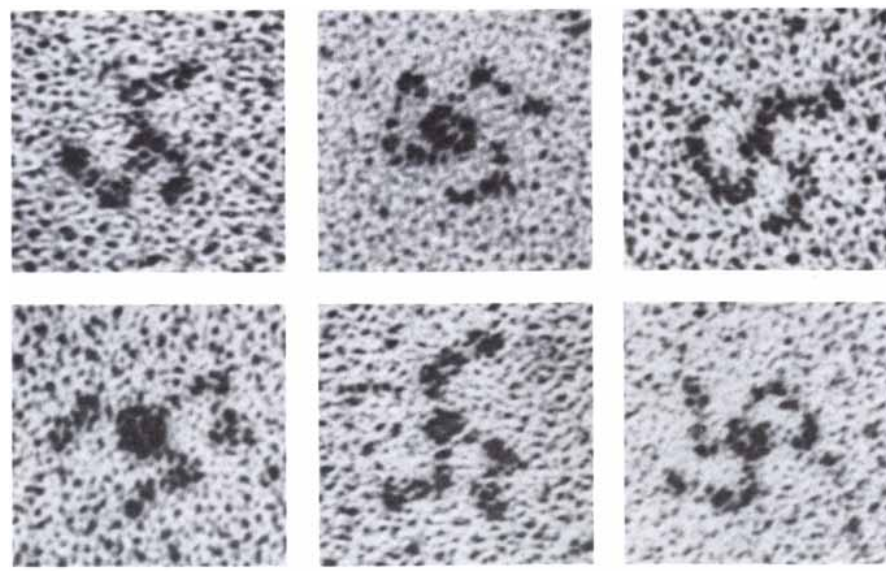
The third adhesion molecule, isolated most recently, is Ng-CAM, which appears later in development and mediates the binding of neurons to the support cells of the nervous system known as glia. The main component of Ng-CAM has a molecular weight of 135,000; two other components, of higher and lower molecular weight, are also isolated by antibodies against this CAM. Ng-CAM is found on neurons but not on the glia to which the neurons adhere. Presumably Ng-CAM binds to an adhesion molecule on glia that remains to be identified. In other words, the binding mechanism is likely to be heterophilic. N-CAM, L-CAM and Ng-CAM do not appear to be cross-specific, that is, none binds effectively from cell to cell to ei-



NEURAL CELL-ADHESION MOLECULE, N-CAM, is diagrammed in its embryonic (*E*) form (*left*) and in its adult (*A*) form (*right*). The protein chain (*color*) has three domains. An amino-terminal (NH_2) domain has a binding region; a middle domain carries negatively charged polysialic acid groups, and a carboxyl-terminal (*COOH*) domain is associated with (probably inserted into) the cell membrane. The *E* form has three times as much sialic acid as the *A* form.



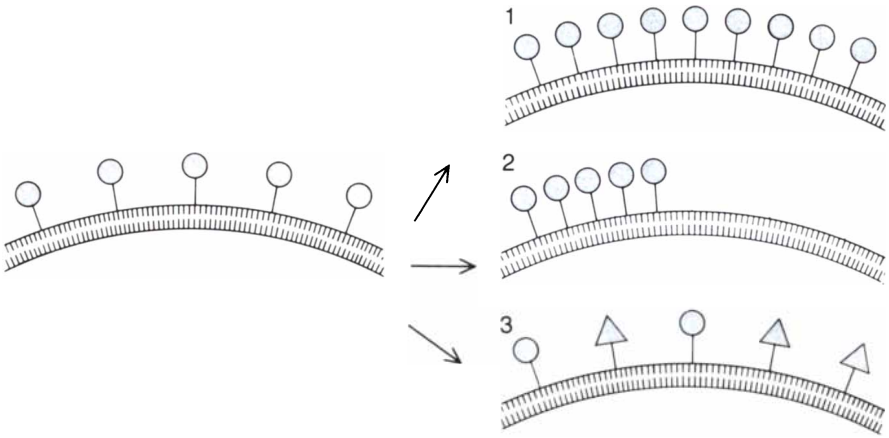
DIFFERENCE IN SIALIC ACID CONTENT is revealed by electrophoresis. Embryonic chick N-CAM (*E*) forms a diffuse band with a molecular weight ranging from 200,000 to 250,000, whereas adult chick N-CAM (*A*) forms two sharp lighter bands (*left*). In another cell-adhesion molecule, L-CAM, no electrophoretic difference is seen between *E* and *A* forms (*right*).



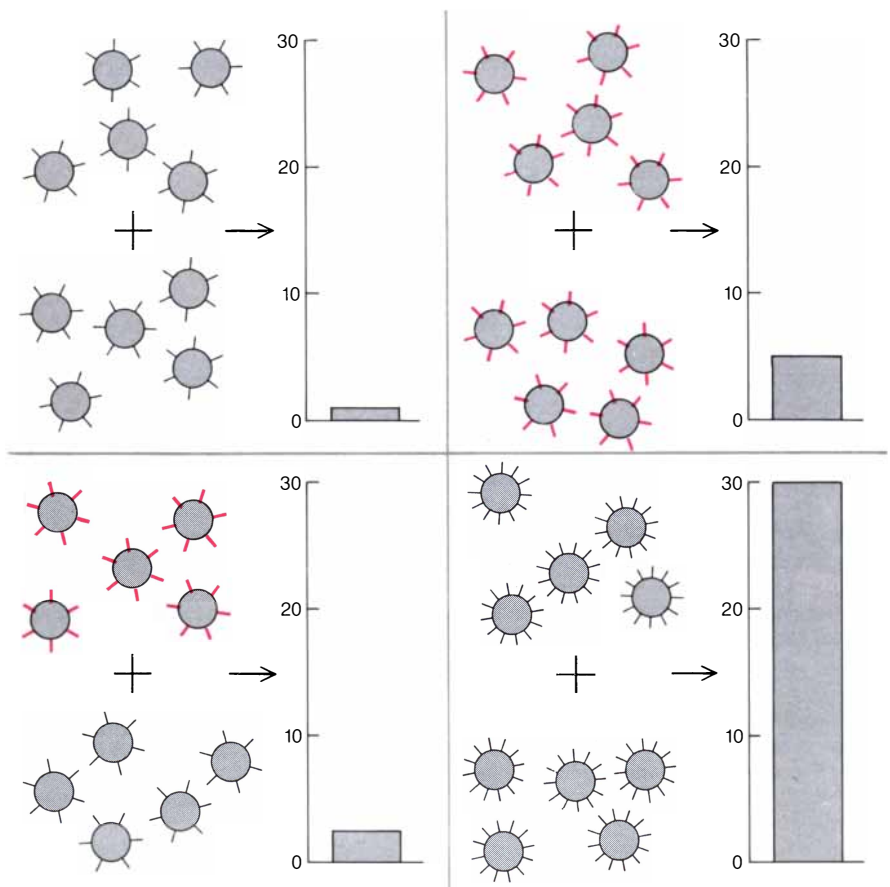
INDIVIDUAL N-CAM'S purified by Bruce A. Cunningham are seen in electron micrographs made by Carolyn Cohen of Brandeis University. Some CAM's mounted on an electron-microscope grid and shadowed with metal form tripartite structures called triskelions, six of which are seen here, enlarged 440,000 diameters. Each arm of the triskelion may be the protein chain of one N-CAM molecule. Whether N-CAM takes this form on the cell surface is not known.

ther of the others. Whether N-CAM and Ng-CAM on the same neuron can interact remains to be clarified.

If the mountain-stream model applies to cellular binding and patterning, there should be mechanisms that alter either the rate or the strength of binding between cell-adhesion molecules present on different cells. In 1976 I proposed that local cell-surface modulation—changes in the amount, distribution or chemistry of particular cell-surface molecules—could bring about such binding changes. These changes would be expected to modify interactions among cells subject to other primary processes such as morphogenetic movements. The altered interactions affecting the primary processes would in turn promote the formation of different patterns. We have found that changes in prevalence do in fact take place in various CAM's during early embryogenesis and that a major reduction in the amount of sialic acid, the *E*-to-*A* conversion, takes place in N-CAM during perinatal development (at about the time of birth in the mouse and of hatching in the chick).



LOCAL CELL-SURFACE MODULATION might alter cell-to-cell binding in three ways. The prevalence of a particular CAM on the surface of a cell could be changed (*1*), its distribution on the surface could be changed (*2*) or the molecule could be chemically modified (*3*), as is the case for the change from the embryonic (*E*) form to the adult (*A*) form of N-CAM.



RATE OF AGGREGATION of artificial lipid vesicles carrying the *E* (*black*) and the *A* (*color*) forms of N-CAM was measured by Stanley Hoffman. The results suggest that two forms of surface modulation can increase the rate of aggregation: *E*-to-*A* conversion resulted in a fivefold increase; a doubling of the prevalence of one form of N-CAM led to a thirtyfold increase.

To demonstrate that such modulatory changes could actually affect binding we needed a direct molecular assay. Stanley Hoffman and I decided to measure the rate of aggregation of various combinations of artificial lipid vesicles into which either the *E* form or the *A* forms of N-CAM had been inserted. We predicted that *E* vesicles would aggregate with one another at a lower rate than they would with *A* vesicles, and that *A* vesicles would aggregate with one another at the highest rate. The prediction was based on the notion that the sialic acid in the middle domain either alters the shape of the binding domain or directly repels the opposing N-CAM molecule from another cell; the less sugar there is, the higher the rate of aggregation should be. The prediction was clearly confirmed.

Even more striking was the effect of increasing the amount of N-CAM of a given form on the membrane. A twofold increase led to a greater than thirtyfold increase in binding rates. Both *E*-to-*A* conversion and changes in surface prevalence can therefore be expected to lead to large changes in rates of aggregation in the course of development, a necessary condition for any kinetically constrained model of pattern formation. It is important to recognize that both of these modulatory changes are essentially continuous, so that they define a very large number of possible binding states for N-CAM. Similar expectations apply to CAM's of other specificities.

How do changes in CAM's relate to alterations in embryonic form? Jean-Paul Thiery, who is now at the Institute of Embryology at Nogent-sur-Marne, and I found that both N-CAM and L-CAM can be detected in the chick embryo very early. Just before the formation of the germ layers the epiblast and hypoblast stain more or less uniformly with fluorescent antibodies to both CAM's. Later on, as the primitive streak develops, the middle-layer cells that are migrating do not stain. At this stage of development a set of remarkable transitions is observed. Cells that will become the neural plate cease to stain with antibody to L-CAM but stain strongly with antibodies to N-CAM. A conjugate change takes place in the surrounding region: a border develops between neural and non-neural ectoderm,

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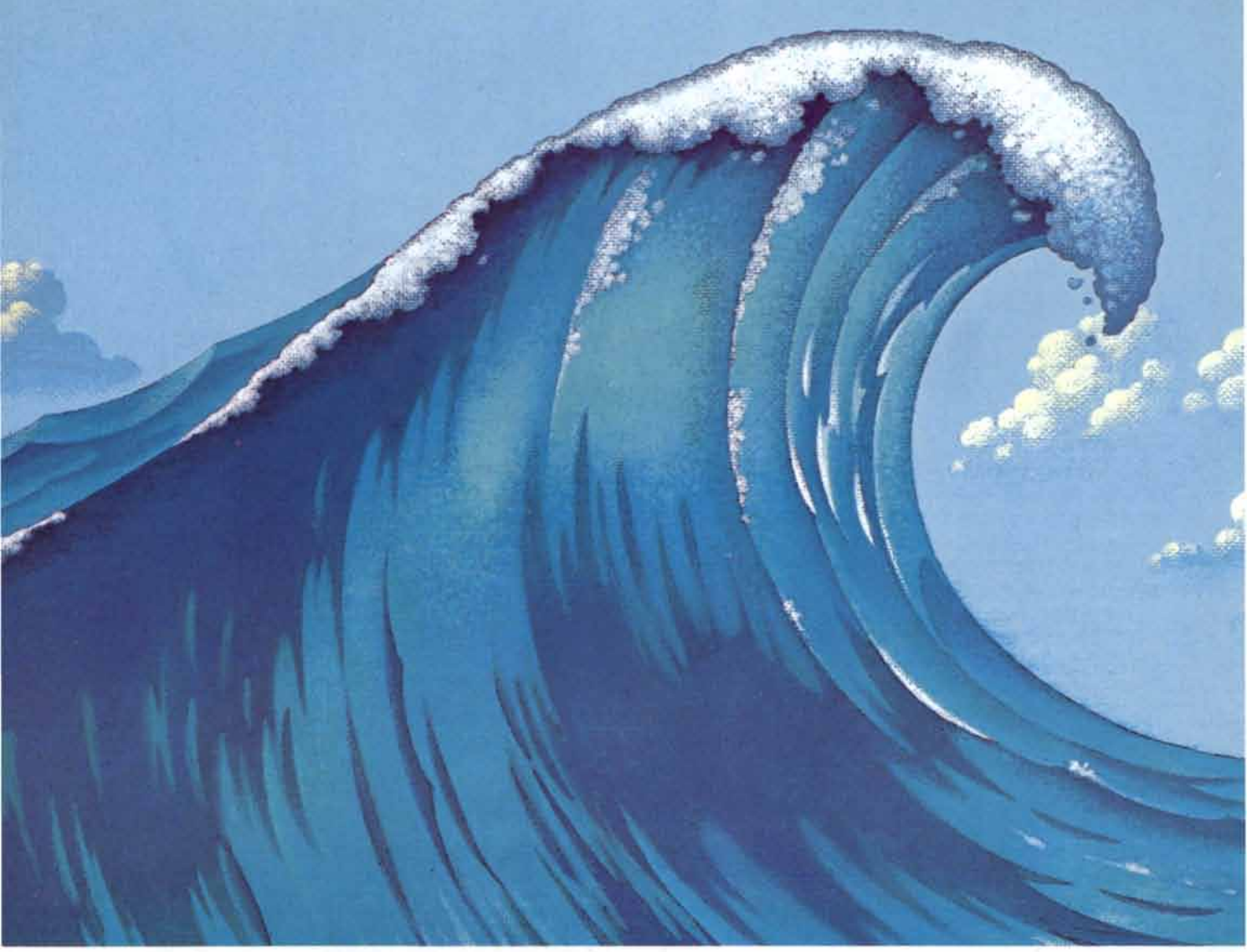

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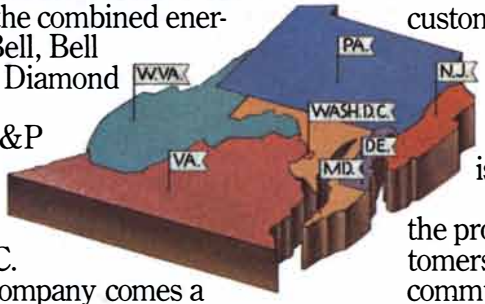

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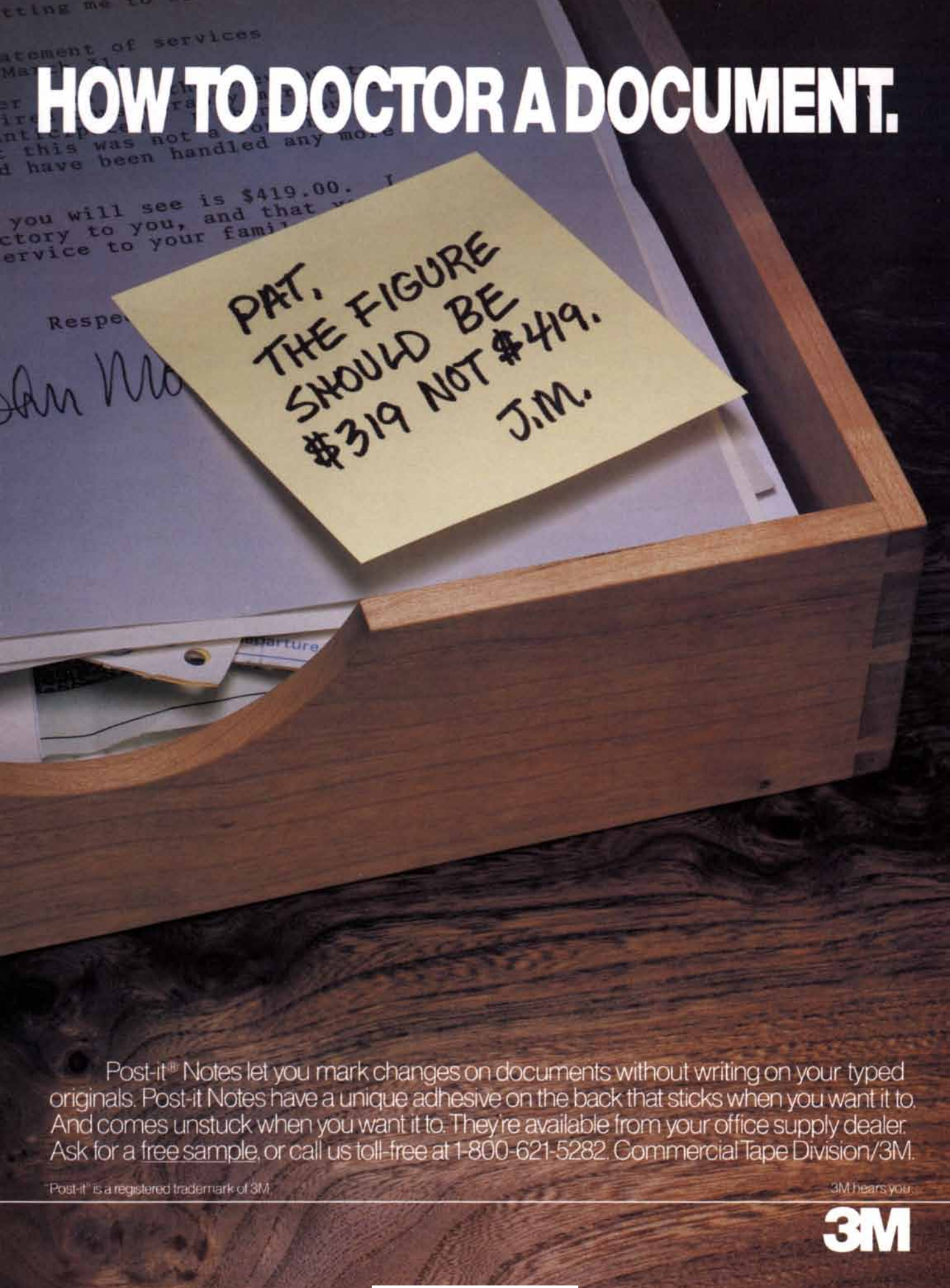

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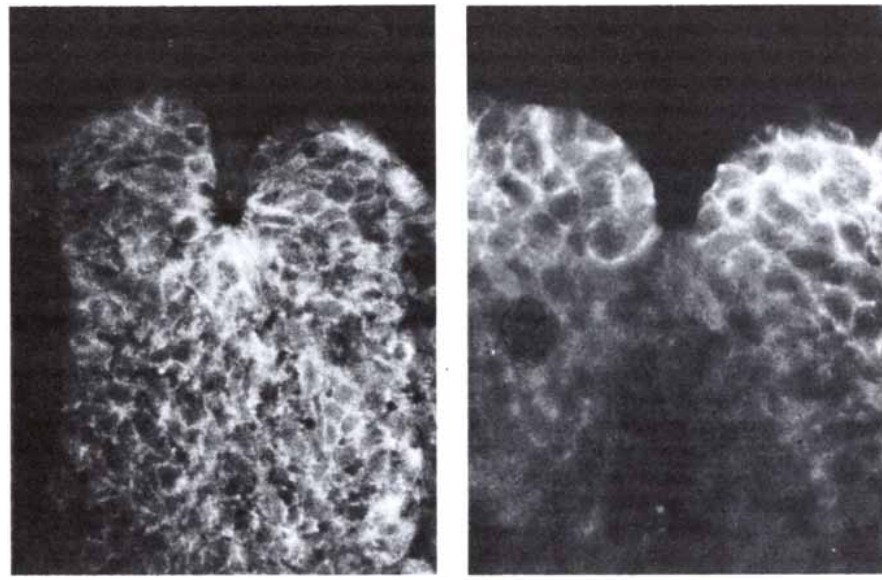
with the non-neural cells staining only with antibodies to L-CAM, as do endodermal cells. The emergence of this pattern of CAM segregation and border formation accompanies the key event of neural induction.

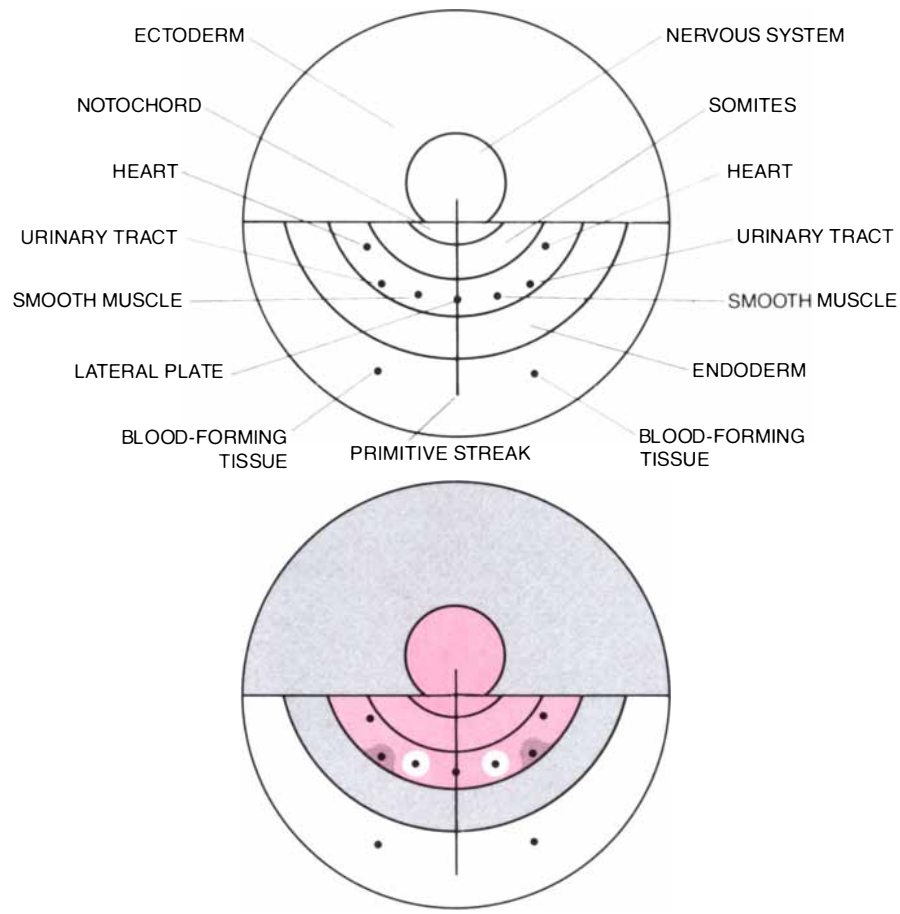
What might these and subsequent changes in CAM distribution mean for pattern? Embryologists make "fate maps" that show what will become of cells in each embryonic region, indicating the tissues and structures they will give rise to in a defined period of time. Luc Vakaet of the Antwerp State University Center in Belgium drew a particularly accurate fate map showing what becomes of chick blastoderm cells by the time organ formation is complete. We traced the CAM expression of those cells and their descendants and constructed a composite CAM fate map by combining our results and Vakaet's [*see bottom illustration at right*]. The composite map has a number of intriguing features. To understand them one needs to recognize that a four-dimensional distribution (time and three spatial dimensions) of cells and CAM markers is being mapped back onto a two-dimensional surface representing the sheet of blastoderm progenitor cells. The result is a topological map rather than a topographic one, with exact details of structure sacrificed to emphasize connectedness and adjacency, the relations that are particularly important for embryonic induction events.

The first striking feature is that the more central N-CAM regions destined to give rise to the neural plate, the notochord, the somites and certain parts of the lateral-plate mesoderm are completely surrounded by a contiguous and connected ring of regions that will express L-CAM; these regions together comprise the non-neural ectoderm and the endoderm. Second, there is a shallow head-to-tail gradient of N-CAM staining. The staining is most intense in the region of the neural plate; in underlying regions such as the notochord it is less intense and the pattern is dynamic: at first there is no staining for N-CAM, then the notochord (a mesodermal structure) stains intensely and finally the stain disappears. A similar sequence of N-CAM appearance and disappearance is observed in the somites.

A third notable succession is observed in the kidney elements that originate in the mesoderm: L-CAM and N-CAM appear and disappear in sequences corresponding to the final stages of the reciprocal embryonic induction of a mass of cells (the mesonephric mesenchyme) by the tubular Wolffian duct. First L-CAM appears on the duct, then N-CAM appears on mesonephric tubules as they organize into epithelia from the mesenchyme, only to be replaced by L-CAM as the tubules subsequently extend. Finally, the map has regions that do not



EXPRESSION OF TWO CAM'S was traced in immunofluorescence studies done with Thiery. Adjacent tissue sections were treated with antibodies to N-CAM (*left*) and to L-CAM (*right*) that had been labeled with a fluorescent dye. In a cross section showing the neural plate as the neural groove forms, N-CAM is present in large amounts in the neural ectoderm at the base of the groove. L-CAM, on the other hand, is confined to the non-neural ectoderm flanking the groove. At an earlier stage the blastoderm stained uniformly for both N-CAM and L-CAM.



FATE MAP based on one made by Luc Vakaet of the Antwerp State University Center shows the origin, on a disk representing the surface of the blastoderm, of cells that give rise to particular tissues and organs (*top*). The fate map was combined with immunofluorescence data to construct a composite CAM fate map (*bottom*) showing the distribution of N-CAM (*color*) and L-CAM (*gray*) and tissues where neither is present (*white*). There is a shallow N-CAM gradient, indicated by two shades of color. Mesodermal cells that form the urinary tract express both CAM's. Note that the central neural-ectodermal regions and some mesodermal regions expressing N-CAM are surrounded by L-CAM regions: non-neural ectoderm and endoderm.

stain at all with antibodies to N-CAM or L-CAM. This suggests that at least one other early-appearing CAM, so far not identified, mediates adhesive interactions in structures deriving from these areas during early development.

Two generalizations emerge. One is that CAM's undergo dynamic changes in the order of their appearance, distribution and amount wherever primary and secondary inductions are under way. The other is that wherever epithelia are converted into mesenchyme, CAM's appear to be lost from the cell surface.

A somewhat fanciful interpretation of the map suggests how some particular patterns may arise. If one assumes that both N-CAM and L-CAM binding are homophilic, then, given the known morphogenetic movements, one can see from the map how the neural plate can roll up and form a closed neural tube as the result of N-CAM interactions and how homotypic interactions among endodermal cells in the interior can form the intestine. The map also suggests how structures such as the intestine and the pharynx can meet the skin even though they originate in different germ layers: what they have in common is L-CAM. Whether these speculations are true or not, the map clearly reveals the topology of CAM expression and the fact that neither CAM is confined to only one germ layer. These findings help to account for several determinants of embryonic form and suggest that the distribution of CAM's and their sequences of expression are critical. Although CAM's do not alone specify shape, it is likely that they provide necessary constraints on the processes that lead to shape.

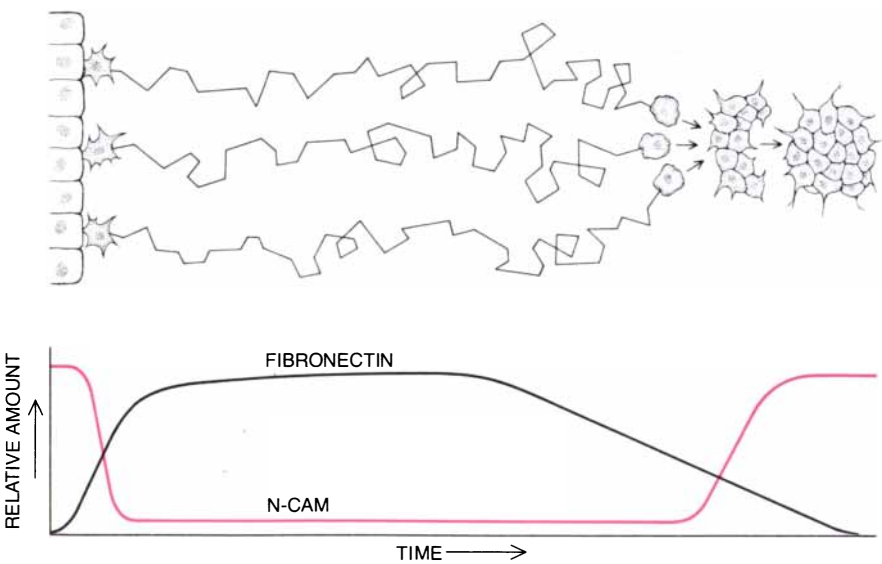
How many CAM's are needed to fill the fate map? So far two CAM's account for more than two-thirds of the early embryonic surface; as I mentioned above, a third primary CAM or even a fourth may be necessary to fill the map, but in any case it appears likely that the number required for early embryogenesis will not be very large. A related question is whether additional CAM's (or different forms of known CAM's) are called into play later to account for refined tissue interactions such as those seen in the later stages of brain development. The answer for the brain appears to be that although N-CAM continues to be active in neuron-neuron interactions in these later stages, at least one new molecule, Ng-CAM, is required for the heterotypic interactions of neurons with glia as the tissue develops.

I now turn to these later events of tissue formation, and specifically to a study of pattern formation in the mouse brain that has provided the most impressive support to date for the surface-modulation hypothesis and for the role of CAM's in the formation of an organ in an intact animal. We reasoned that just as one sees evidence of surface-prevalence changes in N-CAM reflected in the early fate map, so later, within a tissue, one should see the expression of other kinds of modulation. An example would be variations in the extent of the *E*-to-*A* conversion in structurally different neural regions. Although such chemical modulation is local to an organ and is epigenetic, it should nonetheless be under genetic control.

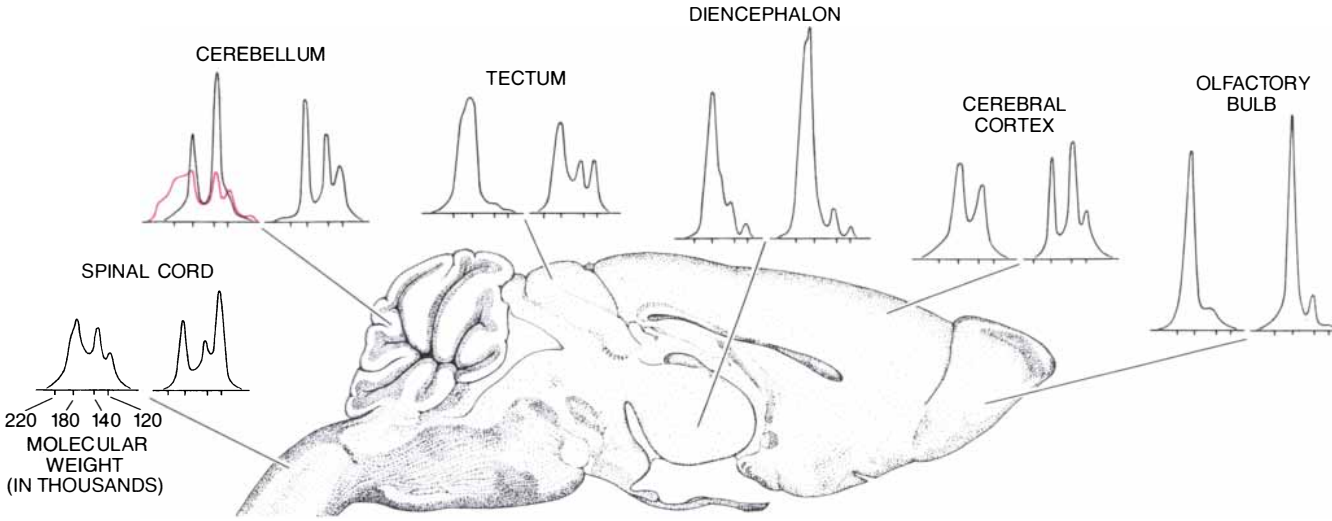
Cheng-Ming Chuong and I found that the pattern of *E*-to-*A* conversion does indeed vary from one histological region of the mouse brain to another. Grossly different relative amounts of the two forms of N-CAM are present in different regions, where the *E*-to-*A* conversion begins at different times or proceeds either at a different rate or to a different extent. Conversion, an epigenetic event, might result in a particular region from the enzymatic cleavage of some of the sialic acid from CAM molecules on the cell surface. Alternatively, it might result from a turnover of CAM on the surface, with the *E* form being replaced by an *A* form to which smaller amounts of sialic acid have been linked by an intracellular enzyme. Whatever the mechanism of this chemical modulation is, the presence of different amounts of the *E* and *A* forms would be expected to change the binding efficiency of differentiating cells in these regions in different ways during histogenesis, altering structure in a dynamic way as both cell differentiation and movement proceed.

Although the *E*-to-*A* conversion is epigenetic and depends on enzymatic activity, the enzymes themselves, like other proteins, are clearly under genetic regulation. To investigate the genetics of CAM regulation and surface modulation we worked with a group of mutant mice discovered by Richard L. Sidman of the Harvard Medical School. These mutants all have defects in the development of the cerebellum; a major symptom is the disorder of motion and balance called ataxia, which begins to appear in the perinatal period. Of the three extensively investigated mutants, *staggerer* shows defects in the connection of neurons to one another; *reeler* and *weaver* have neural connectional disorders that also involve the glial cells, which, as Pasko Rakic of the Yale University School of Medicine has shown, play a key role in the migration of nerve fibers in normal development.

The *staggerer* symptoms and gross defects are seen only in homozygous animals (those in which the genes derived from both parents carry the crucial mutation). In these mice the synapses between the parallel fibers in the cortex of the cerebellum and the densely branched dendrites of the Purkinje cells (which themselves are defective in *staggerer* mice) are faulty. Apparently as a result of the failure in connection, the cerebellar granule cells, which give rise to the parallel fibers, die in great quantities. The consequence of these anomalies is an ataxic animal with a small and disordered cerebellum.



CELL MIGRATION is accompanied by large changes in CAM expression, as was shown in a study of neural-crest cells done with Thiery. These cells originate at the top of the neural tube and migrate widely to form various structures including autonomic and sensory ganglia. In the top part of the drawing typical tracks of three such cells are shown schematically as they move away from the neural tube and eventually join other cells to form a ganglion (*right*). One curve shows how N-CAM, which is present on the cells at their origin, disappears from their surface when they are moving and reappears as they reach their destination and interact with other cells. The other curve shows there is a coordinate rise and fall of fibronectin, a substrate molecule that, Thiery had previously shown, forms a carpet on which the cells move.

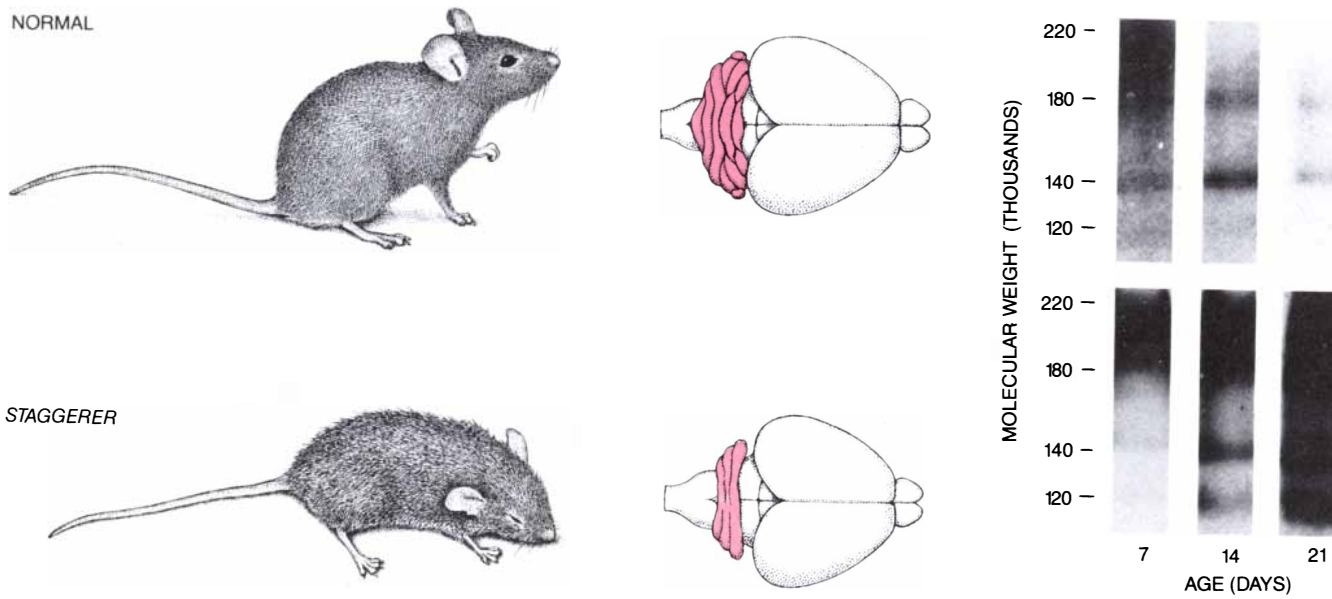


PATTERN OF *E*-TO-*A* CONVERSION varies in different parts of the mouse brain. The differential expression of the embryonic and adult forms of N-CAM is shown for each of five regions by two curves. Each curve represents a densitometer scan of an electrophoretic gel on which the CAM extracted from a particular region was fractionated; the left-hand curve is for 21-day-old mice, the right-hand one for 180-day-old mice. Optical density (and thus the amount of CAM) is shown on the vertical axis and molecular weight is shown on the horizontal axis; the embryonic (*E*) form is plotted at more than 200,000 and the three adult (*A*) forms are at 180,000, 140,000 and 120,000. In most regions there is very little of the *E* form at 21 days and less of it or none at 180 days, but the timing and extent of the conversion are different in different regions. In the mutant *staggerer* mouse the conversion is greatly delayed in the cerebellum (*colored curve*): at 21 days there is still a large amount of the *E* form of N-CAM on cerebellar cells and there is less than the normal amount of the *A* forms.

We surmised that N-CAM modulation was likely to be defective in *staggerer*. This was indeed found to be the case: the *E*-to-*A* conversion is greatly delayed in the cerebellum of the homozygotes, although the N-CAM protein itself appears to be normal. In contrast, *reeler* and *weaver* mutants follow a normal schedule of *E*-to-*A* conversion.

These findings do not yet provide an explanation for the cause of the disease in *staggerer*, but they do suggest that one consequence of the genetic defect is a failure in the synthesis or in the activity of enzymes responsible for the conversion. In normal animals the conversion may increase the level of adhesion and so terminate certain cellular migrations. A defect in conversion could therefore lead to defective coordination of various aspects of nerve-process growth, migration and synapse formation.

As *reeler* and *weaver* show, however, not all connectional defects in the brain (for example those involving glia) need arise only from failures of neuron-to-neuron adhesion. Indeed, it would be expected that neurons must carry surface molecules other than N-CAM in order to mediate their binding to glia, which



***STAGGERER* MOUSE is compared with a normal animal. An animal that is homozygous for the *staggerer* mutation (one that has inherited the mutation from both parents) is ataxic: it has an abnormal posture, moves erratically and loses its balance. Such mice are also smaller and weaker than normal ones, do not groom themselves and die at about 30 days of age. Disorders of cell connections in the cerebellum are reflected in a notably small and disordered gross structure of the cerebellum (*color*). Electrophoretic gels (*right*) document the delay in *E*-to-*A* conversion in *staggerer*. In the normal mouse cerebellum the high-molecular-weight *E* form has been supplanted by the *A* forms of N-CAM by the age of 14 days; in *staggerer* the *E* form persists as a diffuse smear on the gel even at the age of 21 days.**

	EARLY EMBRYO	ADULT
L-CAM	Ectoderm	Skin (germinal layer)
	Mesoderm	Epithelium of urogenital tract
	Endoderm	Epithelia of digestive and respiratory tracts, lymphoid organs and secretory glands
N-CAM	Ectoderm	Nervous system
	Mesoderm	Cardiac muscle, testis

CAM'S PERSIST into adult life in the chick in tissues derived from the germ layers where each appears in the early embryo: all three layers for L-CAM, just two of them for N-CAM.

have key guiding roles in the early histogenesis of both the cerebellar and the cerebral cortex. As I have mentioned, we were able to identify and isolate such a molecule: Ng-CAM. In the chick embryo it appears on central neurons at about three and a half days, just before the definitive appearance of glia in the central nervous system. It would not be represented along with N-CAM and L-CAM in a very early CAM fate map made at three days; in a later map it would appear only in the nervous-system region. It is therefore a secondary CAM confined to certain derivatives of only one germ layer, the ectoderm.

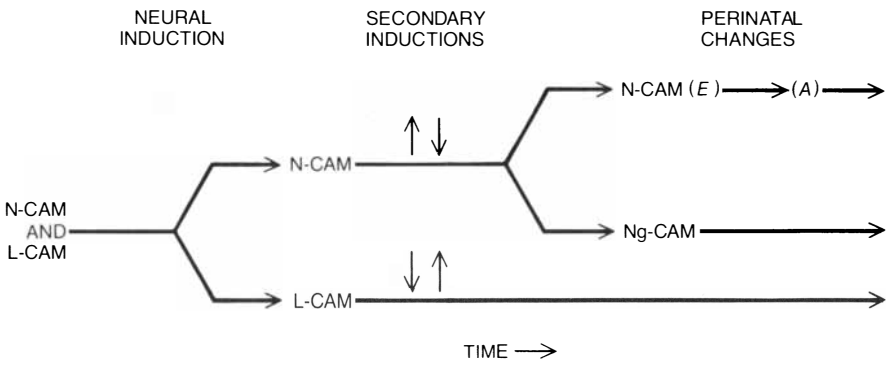
It will be instructive to examine Ng-CAM in the *reeler* and *weaver* mice because it seems possible that either Ng-CAM or a complementary CAM on glia may mediate patterns of neuronal migration on glia and thus be involved in these disorders. We expect to find a new CAM on glia not only because Ng-CAM is absent there but also because the neuron-glia interaction can be expected to be mediated by different CAM's, that is, by heterophilic binding. If the neuron-glia interaction were instead mediated by a homophilic mechanism, there would be complete confusion in distinguishing between simultaneous neuron-neuron and neuron-glia interactions. In spite of the power of modulation mechanisms, it is therefore clear that certain histogenetic circumstances require CAM's of different specificity. It is the combination of specificity and modulation that helps to shape morphogenetic change.

How microscopic can the CAM-mediated morphogenetic shaping be, that is, what degree of precision is it able to achieve within a particular tissue? The brain is the most exquisite testing ground for attempts to answer this question. It will be particularly fascinating, for example, to trace the role of CAM's in forming precise nerve-fiber projections such as those from the retina to the tectum in the brain. Preliminary studies are promising. With Scott E. Fraser of the University of California at Irvine California College of Medicine we have shown that the retinotectal map of the frog *Xenopus laevis* can be greatly distorted in the living animal by the introduction of anti-N-CAM antibodies into the tectum.

Let me summarize our data before proposing a hypothesis relating CAM regulation to the expression of genes and the development of animal form. The majority of the evidence accumulated in our studies supports the idea that local cell-surface modulation is a major contributor to morphogenesis. Several CAM's have been identified. They differ in structure, specificity and mode of binding. The best-studied of them, N-CAM, has a homophilic binding mechanism; neither it nor the other neuronal protein, Ng-CAM, requires calcium ions for binding. In contrast L-CAM, which has a completely different specificity, depends on calcium for binding; it has not yet been definitely shown to be homophilic. These three CAM's are the only ones isolated as purified molecules to date. The question of the total number of different CAM's remains open, but it does not appear likely that a very large repertoire (more than 100) of CAM's of different specificity is required, particularly inasmuch as modulation mechanisms and cell differentiation can greatly alter the selective effects of CAM's on pattern during the course of development.

The dynamic picture of CAM expression that emerges seems to be compatible with the mountain-stream model. During development there is a sequence of both reversible and irreversible expressions of CAM genes coordinated with epigenetic alterations in the surface expression of different CAM's. These events take place at specific places and in a particular sequence in the descendants of particular cells. Although the causal signals for these differential expressions are not known, it is reasonable to suppose that in the course of evolution natural selection has favored individuals in which CAM's were expressed in sequences yielding a functional form. Such sequences would have to be appropriate for each set of cells that takes part in the coordinated series of morphogenetic movements leading to embryonic induction; any failure of induction resulting from a failure of coordination between CAM expression and changes in movement would be lethal. The observed correlation of the L-CAM-to-N-CAM succession with the occurrence of various primary, secondary and reciprocal inductions cannot be accidental.

Whether cell-to-cell adhesion events feed back to affect the primary processes of cell differentiation or cell division directly is not known. It does seem likely that they at least have indirect effects, changing the proportional contribution of each primary process to morphogenesis. For example, a fundamental shaping event in embryogenesis, the epithelial-to-mesenchymal transition, may be accounted for by the prevalence-modulation of CAM's, as in the case of migrating neural-crest cells studied by Thiery. In accord with the basic idea that the early differential expression of CAM genes is necessary for morphogenesis, signals clearly exist to express genes for secondary CAM's such as Ng-CAM at critical times: just before they are needed for heterotypic interactions in histogenesis. It is notable that each CAM persists into adult life only in tissues derived from the germ layer



TEMPORAL SEQUENCE of CAM expression is regulated both genetically and epigenetically. N-CAM and L-CAM diverge in cellular distribution. They are modulated in prevalence (sometimes to the point of disappearance), in particular at sites of embryonic induction. During the formation of detailed nervous tissue a secondary-set molecule, Ng-CAM, appears. In the perinatal period there are additional epigenetic modulations such as *E*-to-*A* conversion.

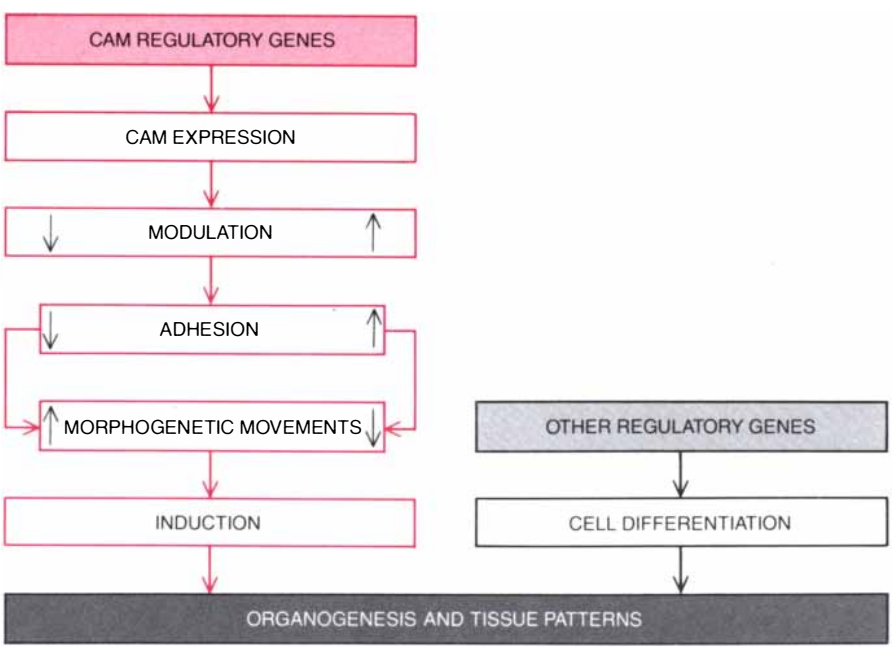
in which it was originally expressed. It would not be surprising to find that alterations in CAM's are associated with a wide variety of disease processes, including the metastasis of cancer cells. Robert Brackenbury, Michael E. Greenberg and I have already shown that N-CAM disappears from neural cells transformed by cancer viruses.

A minimal hypothesis on the molecular basis of morphogenesis must take into consideration three primary processes: cell adhesion, movement and differentiation. (Enough evidence has been gathered in different animals to show that cell division and cell death have important roles in particular kinds of morphogenesis in certain species, but it is clear that local form can sometimes be established without them.) The early expression of primary CAM's must be generally independent of cell differentiation because a given primary CAM appears in induced regions that will only later form different cell types in quite different organs. On the other hand, CAM expression must play a direct role in the control of morphogenetic movement, which results from the interplay of cellular motility, tension in sheets of tissue and adhesion itself.

In the regulator hypothesis I have suggested that the morphogenetic movements that bring cells and tissues with different histories together in embryonic inductions, and so determine succeeding steps of the morphogenetic process, are regulated by the sequences of expression of CAM's. The synthesis of CAM's would seem to be regulated by a special set of mechanisms separate from those that later regulate cell differentiation. What triggers the regulatory genes for CAM's is not known, but when they are triggered, the ensuing series of CAM modulations sharply constrains cell movement and other primary processes. Because development is historical, even the same sequences of expression of L-CAM and N-CAM genes can be expected to give rise to new structures in different contexts of successive cell differentiations.

If the regulator hypothesis proves to be correct, it would be possible to explain why different vertebrate species can have different gastrulation patterns, morphogenetic movements and details in their fate maps and yet share a basic body plan. The proposed reason is that natural selection in the course of evolution allows the survival of only those individuals in which various combinations of morphogenetic movements and CAM-gene expressions lead to appropriate functional inductive sequences.

New CAM's and additional modulating mechanisms will undoubtedly be discovered, greatly enriching and extending this preliminary view of the relation of adhesion to morphogenesis. Enough is known already to say that cell-adhesion molecules of differing specificity, appearing at different times in development as the result of differential gene expression and surface modulation, can act as kinetic constraints on other primary processes of development and so help to establish animal form.



CAM'S REGULATE morphogenetic movement, according to the author's hypothesis. CAM expression is controlled by one set of genes and is modulated epigenetically to promote dynamic changes in cell adhesion; adhesion affects the morphogenetic movements that bring about the induction of organ structures in particular places. A separate set of genes regulates cell differentiation, which interacts within these structures to shape tissue patterns in development.

The Nesting Behavior of Dinosaurs

The discovery of large numbers of dinosaur eggs and skeletons of young dinosaurs at two sites in Montana has led to a novel interpretation of the social relations of these extinct reptiles

by John R. Horner

Dinosaurs are surely the most familiar of all fossil animals. Thousands of complete or partial skeletons have been found on nearly every continent, strewn through strata representing nearly 140 million years of earth history. They have made it possible to infer quite well what the animals looked like. The same cannot be said about how they lived and what their behavior was. Nevertheless, over the past five years dinosaur skeletons and dinosaur eggs have been found at two sites in Montana in associations that yield clues about the social behavior of the three types of dinosaur represented.

The broad setting for the tale is the North American continent of 80 million years ago. The continent was bisected by a shallow sea that has been named the Western Interior Cretaceous Seaway. The newly forming Rocky Mountains, together with a few isolated volcanic systems, made up the highland topography of "West America" and the Appalachian Mountains formed the highlands of "East America."

A broad coastal plain extended from the eastern edge of the Rockies to the western shore of the sea; it was the place where sediments eroded from the mountains were deposited. In what is now Montana and southern Alberta the plain was as much as 400 kilometers wide, although the distance fluctuated with changes in sea level. Along the coast and for some distance inland extensive rivers, river deltas, swamps and marshes were common, bearing dense vegetation that was probably quite similar to what is found on the southern coast of Louisiana today. Bald cypresses, redwoods and numerous broad-leaved trees grew in the wet subtropical climate.

Inhabiting this environment were fishes, amphibians, aquatic turtles, crocodiles and small primitive mammals. Dinosaurs were also present, represented mainly by hadrosaurs (duck-billed dinosaurs), ceratopsians (horned dinosaurs) and numerous small and large carnosaurs. Since dinosaurs are known to have lived there, it is remarkable that the sediments hold only rare and fragmentary remains of dinosaur eggs and juvenile dinosaurs. The remains that are found seem to have been broken up and carried away from some other area.

The scarcity of such fossils in areas where adults clearly lived has been so paradoxical that hypotheses seeking to explain it have been put forward by a number of paleontologists. Some thought the dinosaurs nested in areas subject more to erosion than to deposition. Some said, which amounted to much the same thing, that the dinosaurs must have nested in areas far removed from the coastal plain. Others laid the paradox to the likelihood that dinosaurs had a long life span, so that fewer juveniles were needed to sustain an adult population of a given size.

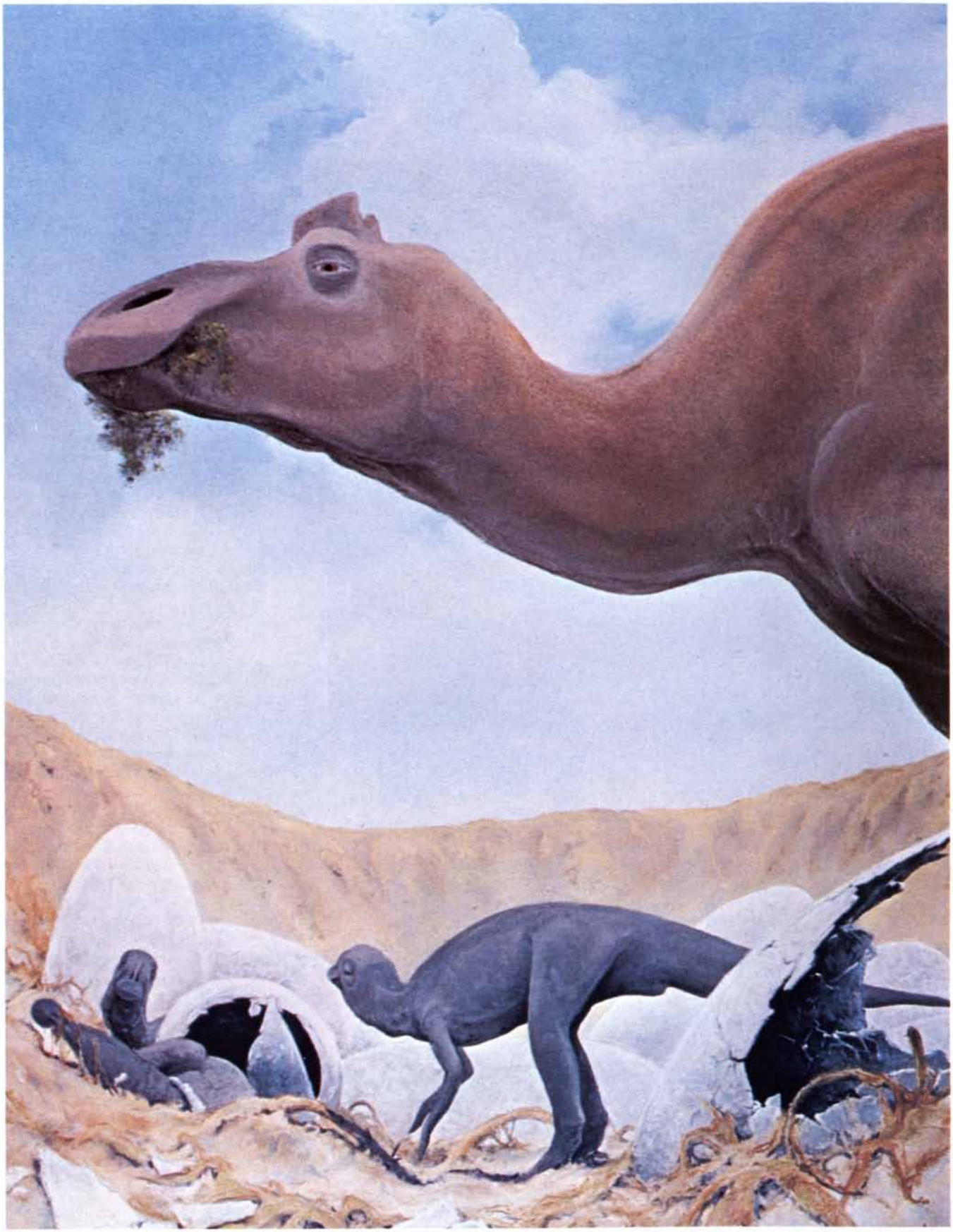
The problem might have been solved long ago if Charles W. Gilmore, a paleontologist with the Smithsonian Institution in the early years of this century, had fully appreciated the significance of one of his own discoveries. Gilmore collected many dinosaur specimens from the late Cretaceous rocks in western Montana known as the Two Medicine Formation. In his field notes he mentioned the abundance of fragments of dinosaur eggs. Moreover, many of the dinosaur fossils he collected and described as representing new species have since been found to represent juveniles of species known from sediments farther to the east.

The Two Medicine sediments differ from those where the remains of adult dinosaurs are found. They were deposited adjacent to the young Rockies in the channels of braided streams and the flood courses of the same streams. Extensive sediments were also deposited in lakes. The tale told by the rocks is that the climate was normally dry at certain times of the year. The striking thing about the many animal remains is the abundance of whole or partial dinosaur eggs and the skeletons of juvenile dinosaurs. Eggshell fragments are the commonest fossils in the sediments, and nearly 80 percent of the skeletal remains of dinosaurs are those of juveniles.

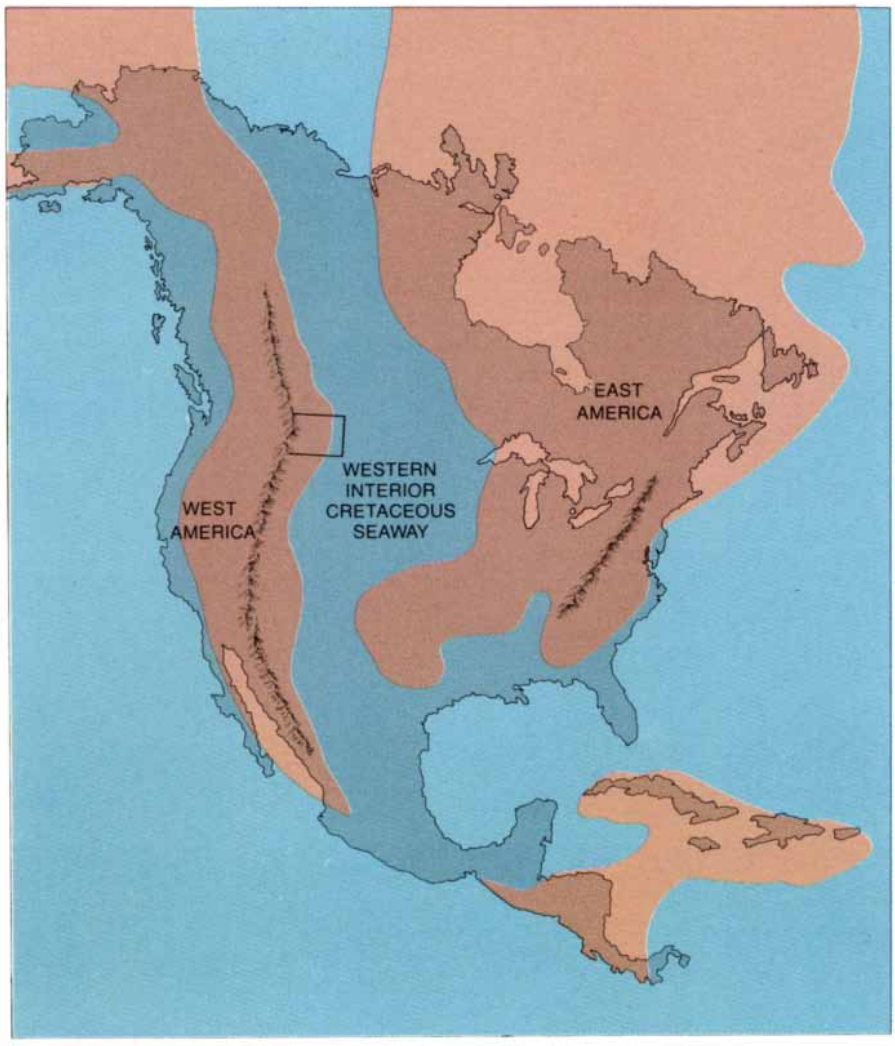
One should bear in mind that the Two Medicine Formation is 650 meters thick and has diverse sedimentary provinces, representing several environments. The site that has been the focus of my own work represents just one environment; the area where Gilmore collected represents another. Although the two environments share more features with each other than they do with the environments to the east, there are still differences between them.

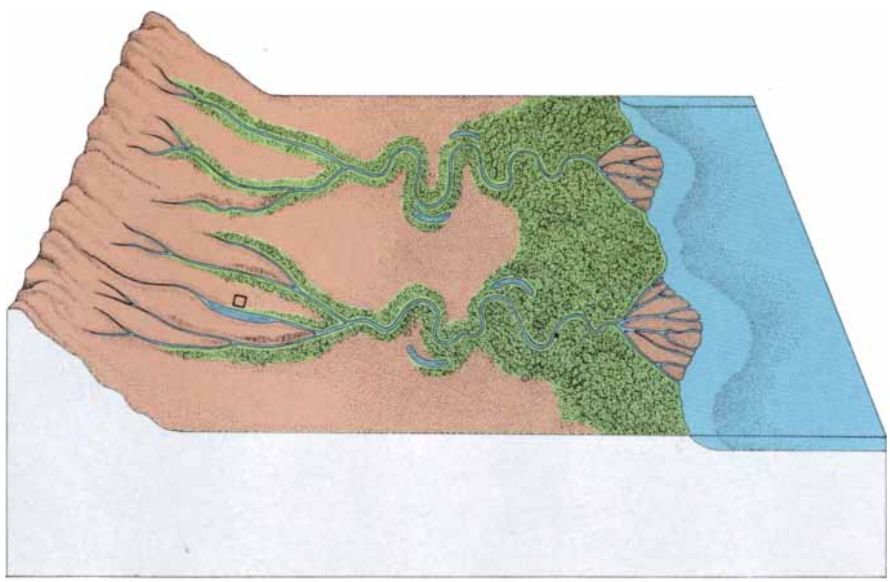
The site where I have worked is called the Willow Creek Anticline. It is less than two kilometers across and has approximately 150 meters of exposed vertical section. The site was discovered in 1978 by Marion Brandvold, an amateur paleontologist from Bynum, Mont. She found what has since been determined to be a nest containing juvenile hadrosaurs. Over the past five years collecting carried out by Princeton University and Montana State University, funded in part by the National Science Foundation, has turned up the remains of nearly 300 whole or partial dinosaur eggs, attributed to at least three different species; the remains of more than 60 whole or partial dinosaur skeletons; numerous remains of lizards and turtles; a large pterosaur (a "flying lizard"), and abundant remains of terrestrial invertebrates. At this site, unlike most other places where dinosaur remains have been found, most of the eggs are in the exact position where they were laid and most of the skeletons are in the position and apparent location where the animal died. Except for one place in the site the remains do not appear to have been disrupted or scattered by streams.

One of the three types of dinosaur egg found in the sediments of the Willow Creek Anticline is attributed to hadrosaurs because fragments were in nests associated with hadrosaur young. The egg, as determined by reconstruction, was about 20 centimeters (eight inches) long and had a lopsided ellipsoi-



VIEW FROM THE NEST of some newly hatched hadrosaurs (duck-billed dinosaurs) is suggested in this idealized scene rendered by artist Doug Henderson, working in close collaboration with the author. According to the author, the evidence he and his colleagues have uncovered indicates that the young dinosaurs remained in the nest until they were old enough to venture forth and forage with the adults. In the meantime seeds, berries, shrubbery and other forms of vegetation brought to the nest by one or both parents may have served as the primary diet of the helpless juveniles. The hatchling was approximately 30 centimeters long and the adult about seven meters.





SHALLOW SEAWAY bisected the North American continent during the Cretaceous period, some 80 million years ago. The broad coastal plain extending from the eastern edge of the newly formed Rocky Mountains to the western shore of the interior sea was inhabited by many species of primitive animals, including the dinosaurs whose fossilized remains were found recently in the vicinity of the Willow Creek Anticline in western Montana, the area delineated by the small rectangle in the map at the top. The site of the discoveries is shown more precisely in the enlarged perspective view of the Cretaceous western American landscape at the bottom.

dal shape. The surface is crenelated, or ridged, with the lowest areas oriented along the length of the egg. Most of the fragments lie in a circular pattern, suggesting that the eggs were laid in a circular nest.

The second type of egg is about 15 centimeters long and more elongated, with barely visible longitudinally oriented striations. These eggs, belonging to a primitive bipedal dinosaur similar to *Hypsilophodon,* are found in circular clutches of up to 24 eggs per nest. The clutches are about a meter in diameter. The eggs are found with their narrower end down, either vertically or obliquely in the sediment. They are distributed in such a way that they do not touch one another except where they have clearly tipped over.

The third type of egg is of unknown origin. It is about 10 centimeters long and has a more regular ellipsoidal shape. The surface is nodular, or lumpy, with no apparent preferred orientation of the depressed areas. The eggs of the third type are found lying horizontally in paired linear rows. The eggs seem to have been completely covered with sediment, in contrast to those from circular nests, which seem to have been only partially embedded in sediment.

Richard Mellon, then an undergraduate at Princeton, examined the different surface structures in relation to the arrangement of the eggs in clutches. He believes the surface structures may have been adaptations for the release of gas. The metabolism of an embryo releases carbon dioxide through pores in the egg. When the egg is partially or completely covered by sediment, however, there must be some way for the gas to get out of the egg and up to the surface. The crenelations and bumps might have served that purpose by holding the sediment away from the pores.

Why is it that some eggs have oriented crenelations or striations and others have a nodular texture with no preferred orientation? Mellon pointed out that the lopsided ellipsoidal eggs were always found more or less upright in circular nests and that they are the eggs with crenelations or striations. Small eggs such as the ones attributed to the hypsilophodonts may not have had enough surface area in contact with the sediment to need anything more than striations of low relief. The hadrosaur eggs had a large surface area and may therefore have needed more relief for the efficient release of gas. The eggs that were completely covered by sediment would have required surface structures regardless of their size. Large eggs found in France and attributed to the brontosaur *Hypselosaurus* have a similar nodular surface. (They also appear to have been laid in linear rows.)

All the known clutches that have been

HADROSAUR NESTING GROUND at the Willow Creek Anticline is swept and screened by members of the author's group to recover every possible eggshell fragment and skeletal part resting at or near the surface. The colored circles on the ground indicate nest sites.

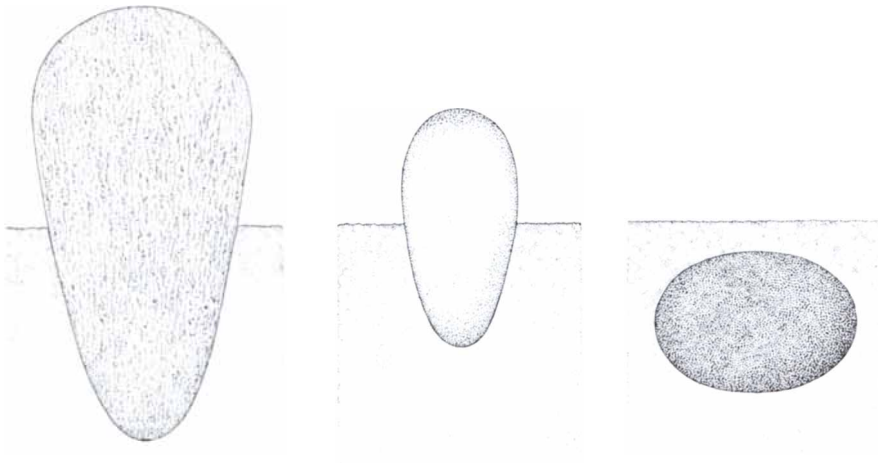
attributed to dinosaurs are either circular or linear. Why? The answer may be related to the social structure of the particular species.

The circular clutches put a concentration of eggs in a small area; linear egg-laying scattered the eggs over a larger area. If, as the evidence suggests, the circular clutches were only partially covered with sediment, the parents (or one of them) would have had to give them attention in order to incubate them and to protect them from predators. The attention would have been costly to the energy budget of the parent, but the survival rate of the eggs was probably enhanced.

The incubation of the eggs in circular clutches was probably achieved by covering the exposed part of the eggs with plant material; this is done by many modern crocodilians and ground-nesting birds. The decaying plant material ferments, generating heat that can be regulated by the addition or removal of material. The eggs laid in the linear pattern were presumably incubated by nothing more than the warming of the ground by the sun. They were probably less successfully hatched because their incubation depended on good weather. It is noteworthy that many of the linear-pattern eggs are found unhatched, whereas most of the eggs in circular clutches appear to have hatched.

It is also noteworthy that the nests of a given species in the Willow Creek Anticline area are found in apparent groups or colonies. The egg clutches of the hypsilophodonts, for example, turn up exclusively on two small hills (facetiously named Egg Mountain and Egg Island). On Egg Mountain all the nests lie within a diameter of about 70 meters. They are in three different sedimentary horizons and are distributed through a vertical section of three meters. Nests on a particular horizon are separated from one another by about two meters. The adult dinosaurs of this species were about two meters long; the nests therefore were rather closely packed. The fact that the nests appear on different horizons implies nesting in the area over a period of years.

The skeletal remains found at the site represent from 20 to 25 hypsilophodonts of various ages. The remains of recently hatched individuals are found not in the nests but scattered among them. The bottoms of the eggs in the nests are intact and uncrushed, so that it is highly unlikely that the young were cared for in the nests; if they had been, the eggshells would have been broken



THREE TYPES OF DINOSAUR EGG were found at the Montana sites. The large ovoid shape at the left is a reconstruction of a hadrosaur egg, based on shell fragments recovered from nests associated with the skeletal remains of juvenile hadrosaurs. The egg is about 20 centimeters long and has prominent, longitudinally oriented ridges on its surface. The somewhat smaller, more elongated egg in the middle apparently belonged to a primitive bipedal dinosaur classified as a hypsilophodont. It has less prominent longitudinal striations on its surface. The egg at the right, of unknown origin, has a nodular, or lumpy, surface. The eggs of the first two types are typically found in an upright position only partially buried in the sediment; the eggs of the third type are usually found lying horizontally in paired linear rows covered with sediment.

up. Why, then, are individuals of diverse sizes found in the nest area? If the young simply hatched and left the area, a couple of individuals might by chance have died before they had gone far, but for as many as 20 or 25 to die seems improbable. One explanation might be that the young, like some ground-nesting birds, remained in the area in groups. The sediments suggest that while this nesting ground was in use either it was on a peninsula extending out into a large lake or it was an island. Perhaps the food of the young dinosaurs was readily available from the lake, so that there was no need for them to extend their feeding range.

Egg Mountain is being quarried layer by layer, with the result that the communities of animal life can be determined for particular periods of time. In the sediments adjacent to most of the hypsilophodont nests one finds clusters of small, oblong egglike structures resembling the pupae of modern carrion beetles. If that is what they are, the beetles undoubtedly fed on dead dinosaur hatchlings and other carcasses and probably on the fluids left in the eggs after hatching.

The remains of predaceous lizards are also found. The commonest ones are varanids, a kind of lizard that in modern times has been observed digging up and stealing eggs from crocodilians and ground-nesting birds. Lizards were probably a major predator on the unhatched eggs of dinosaurs. A third predator of which remains are occasionally found is *Troodon,* a small carnivorous dinosaur, which may have eaten young hypsilophodonts.

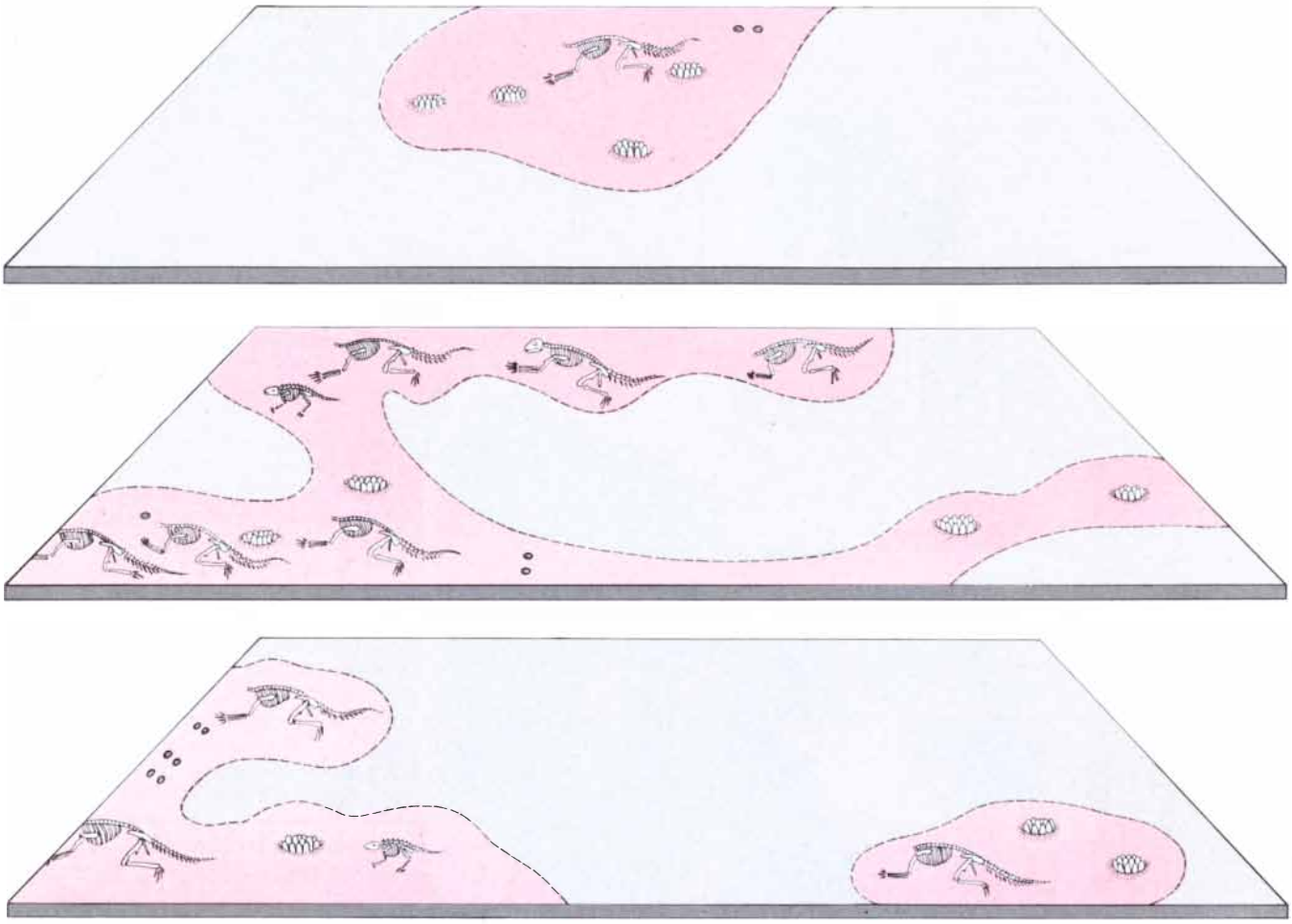
Also found almost exclusively at Egg Mountain are the linear-row dinosaur eggs. Although a good many eggs have been collected, it is not clear how many clutches they represent because of the unusual way they are scattered. It may be that the linear pattern is a trait distinguishing the two orders of dinosaur: Ornithischia (mostly herbivorous) and Saurischia (mostly carnivorous). Hypsilophodonts, the duck-billed dinosaurs, the horned dinosaurs and others belong to the Ornithischia, carnivorous dinosaurs and brontosaurs to the Saurischia.

Eggs attributed to the horned dinosaur *Protoceratops* (from Mongolia) are found in circular nests, as are those attributed to the hypsilophodonts. The evidence of both shell structure and nest shape suggests that the nests of the hadrosaurs were also circular. The brontosaur *Hypselosaurus* found in France, a saurischian, apparently laid its eggs in rows. It may therefore be that ornithischians laid eggs in cirçular clutches and saurischians laid them in rows. Perhaps the eggs found at Egg Mountain in a linear pattern were laid by *Troodon,* which as a small predaceous saurischian would have had an exceptional advantage by hatching in the nesting ground of nonpredaceous dinosaurs.

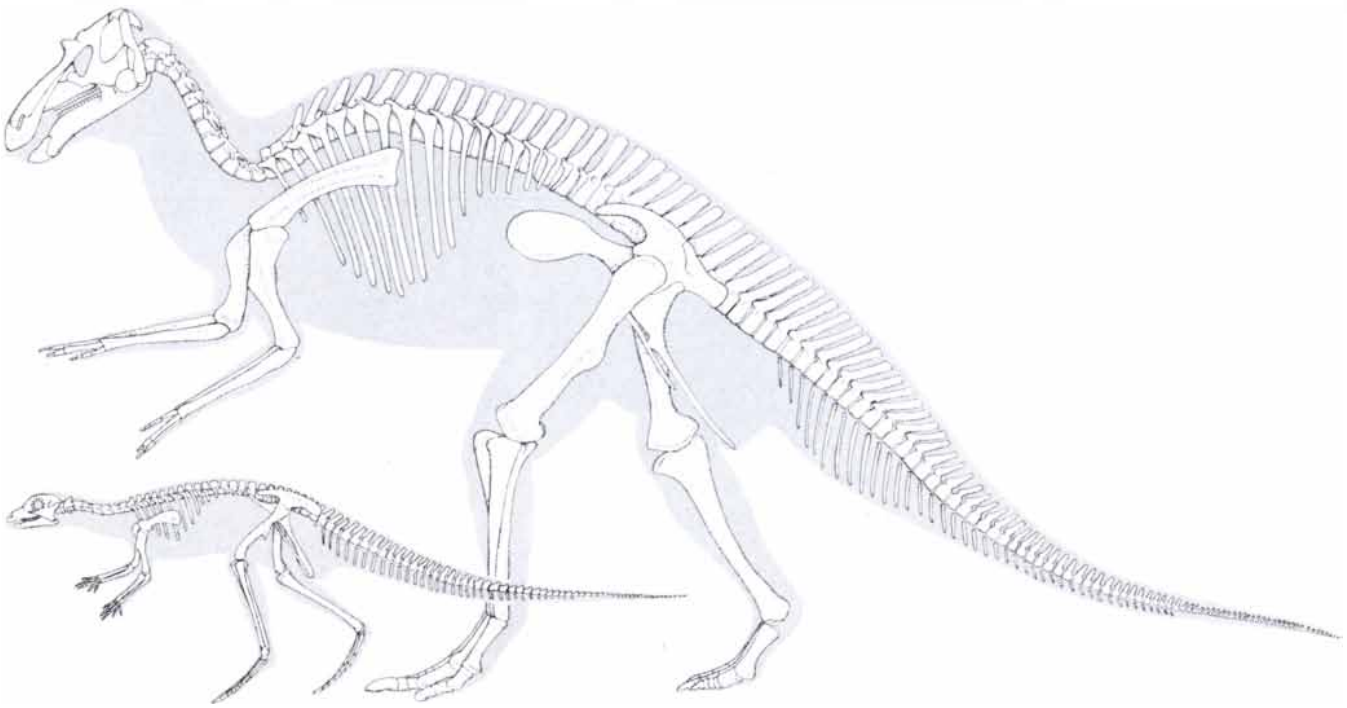
CLUTCH OF 24 EGGS was removed intact from a hypsilophodont nest on a small hill known as Egg Mountain. The view is of the bottoms of the eggs. The scale bar is five centimeters long.

Egg Island, as its name implies, is completely surrounded by lake sediments. Although the lake may not have been very deep or even continuous throughout the time the island served as a nesting site for dinosaurs, it probably afforded a degree of protection from predators. The site was discovered in the last week of the 1983 field season and therefore has not been as extensively excavated as Egg Mountain. Already, however, it has yielded three clutches of hypsilophodont eggs in two separate horizons. One of the clutches consists of 19 unhatched eggs, each egg containing the skeletal remains of an embryo. The skeletons are all the same size, suggesting that the eggs of the clutch were laid at the same time and would have hatched simultaneously.

Yet another site in the Willow Creek Anticline is proving to be even more informative in some respects than Egg Mountain and Egg Island. About a kilometer from Egg Mountain, in floodplain sediments that were laid down earlier, are the remains of a hadrosaur nesting ground. Eight nests have been found so



SCHEMATIC DIAGRAM OF EGG MOUNTAIN reveals several levels of dinosaur nests and skeletal remains. The colored areas show the extent of the excavations; the gray areas are either still covered with sediments or eroded away. The circular groups of eggs in the shallow depressions are hypsilophodont clutches. The small dark ovals are the dinosaur eggs of unknown origin. The skeletons with the long hind limbs are the remains of hypsilophodonts. The other skeletons are lizards, possibly predators. The vertical scale is exaggerated.



SKELETAL RECONSTRUCTIONS of an adult hadrosaur and an adult hypsilophodont are drawn to the same scale in this illustration. In contrast to the hadrosaur, whose top speed was probably a slow waddle, the hypsilophodont appears to have been a swift runner.

far. They all appear to have held eggs at about the same time, since the nests are all on one sedimentary horizon.

Hadrosaurs were much larger than hypsilophodonts, the adults averaging seven meters in length. Their nests were also larger, about two meters in diameter and one meter deep. The nests appear to have been built up from the ground. They were probably made primarily of mud. Shaped like a bowl, they were apparently intended to hold a circular clutch of eggs. The size of the nest and the eggs, taken together with the assumption that the hadrosaurs arranged their nests much as the hypsilophodonts did, suggests that a clutch would have consisted of from 20 to 25 eggs.

The hadrosaur nests, like the ones made by the hypsilophodonts, were closely packed, separated one from another by about the length of an adult. They differ from the hypsilophodont nests, however, in containing not the intact bottoms of eggs but an abundance of fragmented eggshell. Two nests also held the remains of juveniles. One nest, which was badly weathered, held seven juveniles, each only .45 centimeter long; the other nest held 15 individuals, each about one meter long. (At hatching a hadrosaur was from 30 to 35 centimeters long.)

Hadrosaurs were bipedal herbivores with no obvious means of defense except possibly kicking and stamping with their hind legs. They did not have horns, plates, spikes or an armored skin. The skeletons suggest that the top speed of the animals was a slow waddle. Presumably the young in particular would have been exceedingly vulnerable to predation. The abundance of hadrosaur remains in late Cretaceous sediments, however, suggests that they were among the most successful of all dinosaur groups. How did they do it?

What the evidence implies is that hadrosaurs nested in large, densely packed colonies and guarded their eggs. After the eggs hatched the adults stayed to guard and feed their respective young. Like altricial birds, whose young are also born helpless, the juveniles remained in the nest until they were large enough to forage with the adults.

Hadrosaur adults were also apparently able to alert other members of a colony or a herd by sounding vocal alarms. Evidence that they could vocalize has been presented in independent studies by James A. Hopson of the University of Chicago, David Weishampel of Florida International University and me.

These speculations would not gain the assent of everyone who has studied dinosaurs. Presumably few would argue against colonial nesting, the guarding of eggs or vocalizing among adults, since these behaviors are observed among liv-

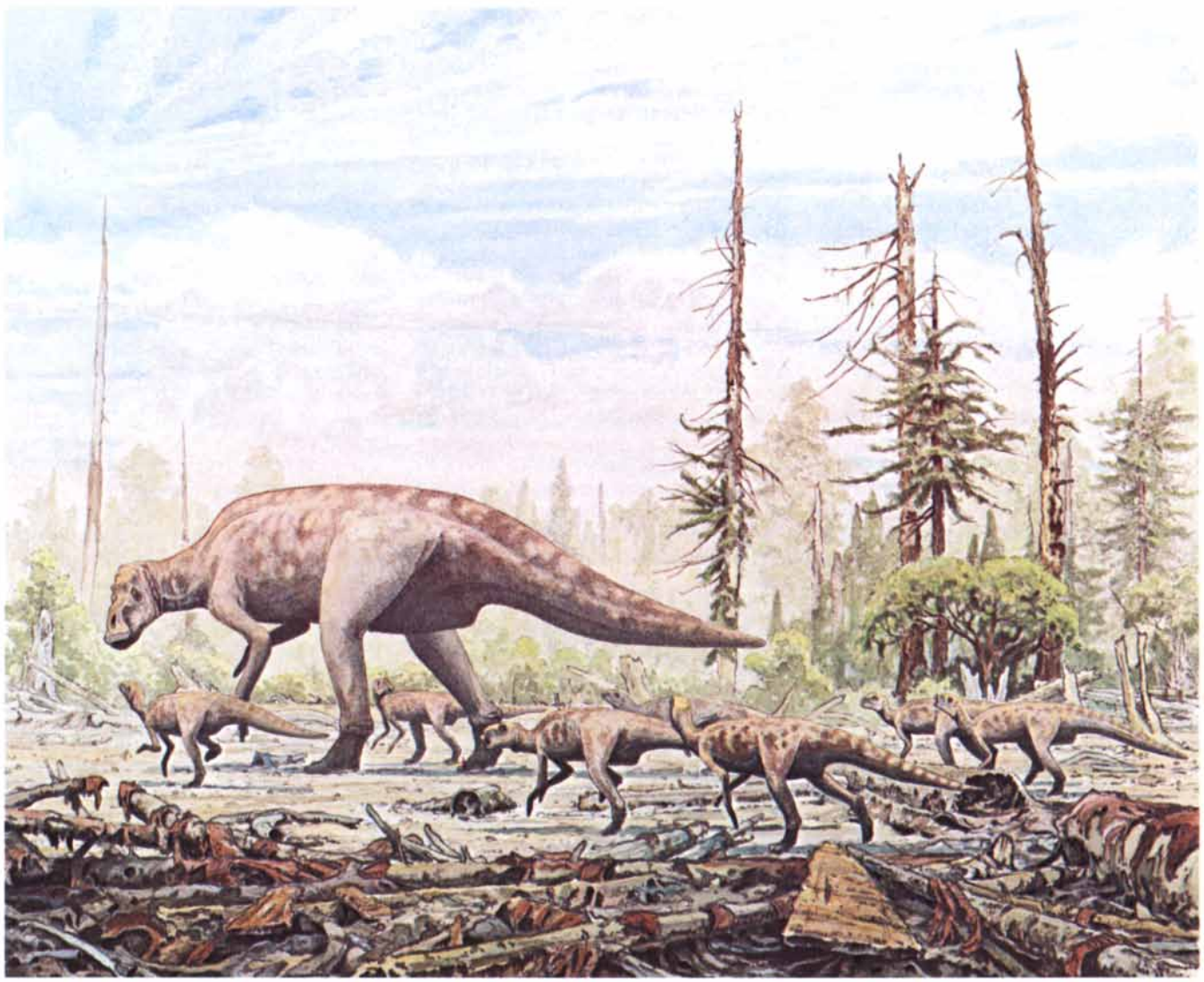
ing crocodilians. Food sharing is another matter, documented mainly among birds and mammals. Many scholars think the dinosaurs are being credited with a more complex physiology and more kinds of behavior than are probable for any living or extinct reptile. They would probably reject the hypothesis of food sharing because it is extremely rare among living reptiles.

The question is whether living reptiles are incapable of this behavior and other behaviors or whether they simply do not need them. Many scholars believe basic behaviors are passed from one generation to another through the genes. Even though an animal might not display a particular basic behavior, it might be capable of doing so if the need arose. For example, animals such as the crocodilians may be capable of sharing food but have no need to do so. Crocodilians are predaceous and aggressive even when they are young. Herbivorous infant dinosaurs, such as the hadrosaurs, were clearly not only nonaggressive but also highly vulnerable to many predators. The parents would have had to share food with the infants and to provide extended supervision.

The sediments of the Willow Creek Anticline also provide evidence that the hadrosaurs remained in herds or some other form of social aggregation throughout much if not all of their lives. In six separate localities the remains indicate an association between adults and juveniles. The fact that the juveniles are no more than half the length of the adults suggests that subadult individuals (from three to six meters long) may have left the group to roam in other areas.

Although these interpretations are conjectural, they are supported by the evidence of the sites and by logic. The mere presence in nests of young hadrosaurs of the same size implies a situation quite different from anything that could be explained by stream transport. The young appear to have died in place, and they show no evidence of having been killed by predators. If young altricial birds are abandoned by their parent or parents, they starve. Moreover, feeding in the nest seems likely because of the high mortality that would have resulted otherwise. The skeletons of hatchlings differ from those of adults only in size, and so it is assumed that the young were no more able than the adults to run fast or to execute other defensive maneuvers. Juvenile success was most likely achieved because adults fed the young from the edge of the nest, with additional protection provided by dense colonization. Herding would have been a continuation of the hadrosaurs' aggregational behavior.

As for the hypsilophodonts of Egg Mountain, feeding in the nest by the parents may not have been necessary. The skeletal morphology indicates that these animals were fast runners. Their primary defense against predators may have been a quick getaway.



YOUNG HADROSAURS, just out of the nest, are portrayed foraging with a single parent, presumably the female. Foraging may also have been done in the company of other members of the herd. The rendering, a lithograph with watercoloring, also is by Henderson.

Prehistoric Rice Cultivation in Southeast Asia

Recent archaeological work in the region demonstrates that the domestication of the grain led to the rise of city-states and the development of trade contacts with India and China

by C. F. W. Higham

Rice is a foodstuff that sustains more than half of humanity, yet hardly anything is known about its earliest domestication. The beginnings of barley and wheat cultivation in the Neolithic Near East and of maize cultivation in Mesoamerica are comparatively well documented archaeologically, as is the fact that grain domestication in both areas underwrote major population expansions and the rise of urban states. Similar information on rice, however, has been at best scanty until recent archaeological work in Southeast Asia began to reveal at least part of the record.

It is my aim here to report the present state of archaeological knowledge with respect to rice cultivation in the region. A primary question concerns the place or places where rice first became a staple of subsistence. A second concerns the processes that may have made it a staple. Finally, if Southeast Asia was indeed the initial site of emergent rice cultivation, what evidence is there of a similarly emergent local civilization, as in the Near East and Mesoamerica, before the high cultures of India and China put their own stamp on the region toward the end of the first millennium B.C.?

It is necessary at the start to touch on the geography and botany of the region and its recent geologic past. Three major rivers traverse the area: the Red River, with its delta on the Gulf of Tonkin, the Mekong, whose many mouths dominate Cambodia and southern Vietnam, and the Chao Phraya, which turns Bangkok, the capital city of Thailand, into a kind of Venice before it empties into the Gulf of Thailand. Rice still grows wild in the three valleys and the valleys of the rivers' many tributaries. In neighboring China rice came under cultivation in the lower Yangtze valley by about 5000 B.C., so that it is quite possible a similar development took place in the river valleys of Southeast Asia.

Major changes in sea level, associated with the melting of the Pleistocene ice sheets, drowned large areas of the region that were formerly dry land. For example, some 7,000 years ago the sea level was several meters higher than it is today; the sea began to recede to its present level only between 2,000 and 3,000 years ago. Thus whatever sites of human habitation there may have been on the Ice Age coast are now, so to speak, high and dry. Moreover, archaeological sites in the limestone uplands of the region have remained undisturbed. Still, the hill caves that have been excavated, such as Spirit Cave in northern Thailand (studied by Chester Gorman of the University of Pennsylvania) and the caves in the northern Vietnamese province of Hoa Binh, present only a partial view of prehistoric life in the region.

The people who sought shelter in the upland caves were mostly small groups of hunters and gatherers. The terrain is so well suited to such a way of life that many bands of hunters and gatherers roamed the region well into historical times, and a few still do so today. In fact, Spirit Cave is perhaps the last place in Southeast Asia to look for the origins of rice cultivation. It lies in fine hunting country but is perched on a steep slope, far away from the nearest running water. Even though the cave soils were carefully sifted, Gorman found no rice in them.

In the coastal strip below the uplands of Hoa Binh the situation is quite different. Excavations in areas well back from the present shoreline have revealed numerous large sites of human habitation that stood on or near the ocean at a time when the postglacial sea level was at its highest. Surveys have indicated that the same is true along the margins of the Gulf of Thailand.

The single most important early site in the Thai coastal area, Khok Phanom Di, is now more than 20 kilometers from the shore. In the centuries between 5000 and 2000 B.C., and perhaps over an even longer span, the site was on or near a coastal mangrove swamp. Its occupants fed on the fish, mollusks and crustaceans adapted to life in the brackish waters among the mangroves. The debris of human occupation eventually left a midden more than 12 meters high and about five hectares in area. Within the midden, in a clearly defined stratigraphic sequence, are graves whose occupants had been sprinkled with red ocher before burial and were accompanied by personal decorations, polished stone axes and pottery. Pottery and potsherds have been found at all levels of the site, and analysis of sherds some five meters below the present surface shows that the clay was tempered with rice chaff.

A major campaign is now being planned for Khok Phanom Di, sponsored jointly by the Fine Arts Department of the Thai government and by my own institution, the University of Otago in New Zealand. One of its principal objectives is to test the hypothesis that the midden builders may have taken to active rice cultivation when the receding ocean left them stranded, as it were, an uncomfortable distance from their marine foodstuffs. The use of rice chaff to temper pottery is not, of course, clear evidence of rice cultivation. The people of Khok Phanom Di surely gathered wild rice, along with other wild plant foods, to supplement their diet.

One can, however, be sure of one fact.

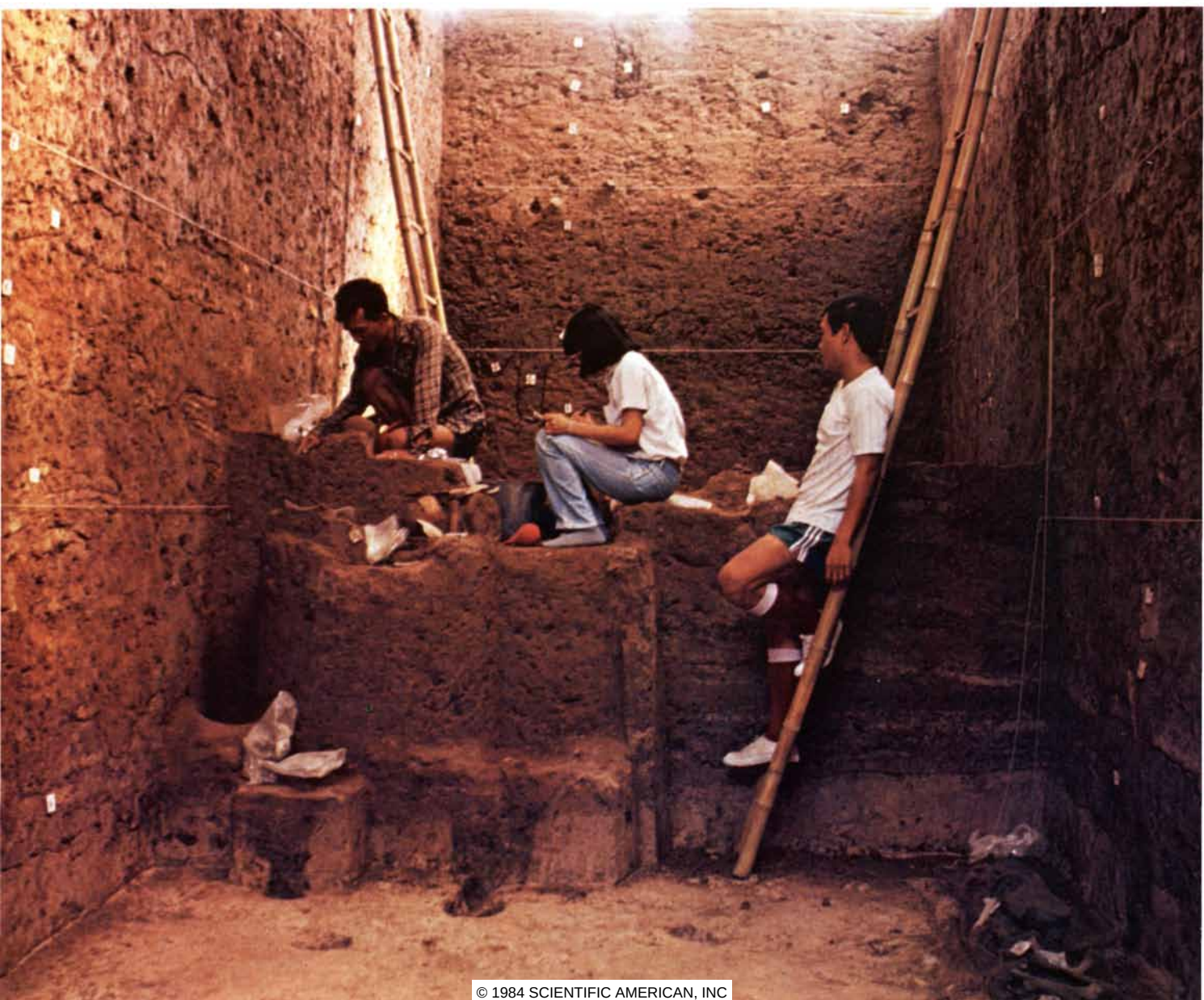
EXCAVATION AT BAN NA DI, a small village site in northeastern Thailand that was first occupied in about 1400 B.C., is seen in the photograph on the opposite page. Its inhabitants grew rice and raised pigs and cattle. They were also good potters and bronze casters who buried their dead in the same cemetery over a period of about 1,000 years before abandoning the site.

Whether or not the people of the midden had become rice cultivators before they abandoned the site in about 2000 B.C., rice was being grown elsewhere in Southeast Asia by or before that date. Recent excavations on both sides of the mountains of Annam show this to be the case. More than 50 small agricultural settlements have been uncovered by Vietnamese archaeologists on the eastern side of the mountains, in what is known as the "middle country" upstream from the Red River delta. On the western side, in the middle Mekong valley, archaeological work at three Thai sites—Non Nok Tha, Ban Chiang and Ban Na Di—has revealed that this area was also penetrated and settled by agriculturists.

In both areas the new settlements were in places that show no trace of earlier hunter-gatherer habitation. The pioneer farmers chose slightly elevated ground for their villages, locales with easy access to low, regularly flooded wetlands. The terrain inland from the Red River delta was ideally suited to such settlement. Numerous low hills command a stream that is tributary to the region's major waterway. The excavations at one of these middle-country sites, Phung Nguyen, show that the settlers combined rice cultivation with animal husbandry and hunting. They were also excellent potters and proficient workers in stone. The site's name has been given to the transitional Neolithic culture of the entire middle-country region that extended from about 2500 to 1800 B.C. Only the most recent layers of a handful of Phung Nguyen sites hold small fragments of metal; they are bronze.

In addition to the three major sites in northeastern Thailand, recent surveys have located numerous village sites distributed in the same pattern as those of the Phung Nguyen culture: on the middle courses of small tributary streams. The earliest of these settlements, established in about 2400 B.C., seem to have covered only a hectare or so and could hardly have had more than 50 or 100 occupants. The economic pattern was also quite similar to the one on the other side of the mountains. Rice was grown in seasonally flooded valleys; cattle, pigs and dogs were raised, and the diet was supplemented by the products of hunting and fishing. Because the climate of northeastern Thailand has a six-month dry season, broken by the onset of the monsoons, the settlers' survival must surely have called for the storage of much of the rice harvest for dry-season consumption. In any event, as seems to be the case around the world, the early farmers' settled way of life was followed by a period of population increase, the growth of hamlets into larger villages and the establishment of additional settlements in a kind of continual fissioning.

The excavations at Ban Na Di present a clear view of the process. A small hamlet some 20 kilometers from the larger village site of Ban Chiang, Ban Na Di was first settled in about 1400



MARBLE BRACELET from the cemetery at Ban Na Di is one of several ornaments made out of materials imported from distant sources. The value of the bracelet is indicated by the fact that after it was broken it was mended with bronze wire strung through pairs of holes.

FIGURINE OF A BULL is also from Ban Na Di. It is about 15 centimeters long and is one of a number of such clay figures, including a few of human beings, found in the cemetery.

B.C., perhaps 1,000 years after the establishment of its larger neighbor. The material culture of Ban Na Di is so much like that of Ban Chiang in spite of the smaller site's later date that Ban Na Di could well have been founded as a result of overpopulation at Ban Chiang.

Ban Na Di never covered more than three hectares, and its maximum population could hardly have exceeded 150. In addition to a knowledge of rice cultivation its founders brought with them the technology of casting bronze. The products were mainly axes and arrowpoints, and almost all the stages of casting have been uncovered. The making of molds was of course the necessary first step. This the metalworkers did by carving a two-piece master mold out of sandstone. They did not pour the molten bronze into the master. Instead they filled it with lead, which has a much lower melting point than bronze and was less likely to crack the stone. The lead casts were then invested with clay. When the clay and the lead were heated together, the clay was baked hard and the lead ran out. The clay molds were then filled with bronze. The metalworker prepared the bronze by placing the wanted proportions of copper and tin in a clay crucible that was heated in a charcoal-filled furnace under a forced draft. In the early levels of the Ban Na Di site we found the furnaces, the crucibles, fragments of the sandstone molds and even a fragment of one of the lead casts.

Nearly all the bronze artifacts at Ban Na Di, however, were found in the village cemetery. Indeed, it is the human remains and the objects accompanying them that tell the most about village life. The same area served as a burial ground almost from the founding of Ban Na Di until its abandonment in about 400 B.C. The dead were interred, together with their personal adornments, lying on their back with their legs extended. Mortuary furnishings included intact pottery filled with foodstuffs such as rice, fish and in one instance the forelimb of a young pig. Some of the vessels that contained no food may have held drinking water or other liquids. Evidently an interment was the occasion for an animal sacrifice; in most instances the left foreleg of an ox or of a pig was placed beside the body.

Many of the decorative objects—anklets, bracelets, and necklaces—were made out of imported materials. For example, one man was buried with 14 shell bracelets. The shells are of the marine genus *Trochus,* an inhabitant of clear waters that is found today only off peninsular Thailand, 1,000 kilometers south of Ban Na Di. Other bracelets were made out of marble, the limestone travertine and slate. None of these materials is to be found locally; their presence, like that of the marine shells, in-

IMPORTANT SITES in Southeast Asia range in age from hunter-gatherer hill sites such as Spirit Cave and the early midden site of Khok Phanom Di that are 7,000 or more years old to first-millennium-A.D. city sites such as Oc Eo and Angkor that reflect Indian influences and international trade. The shaded region west of modern Hanoi is the hilly uplands of Hoa Binh province. There numerous hunter-gatherer sites have given the name Hoabinhian to this phase of Southeast Asian prehistory, just as the Bronze Age site of Dong S'on has given its name to the many recently discovered Bronze Age sites of the Red River area, such as Viet Khe and Chau Can.

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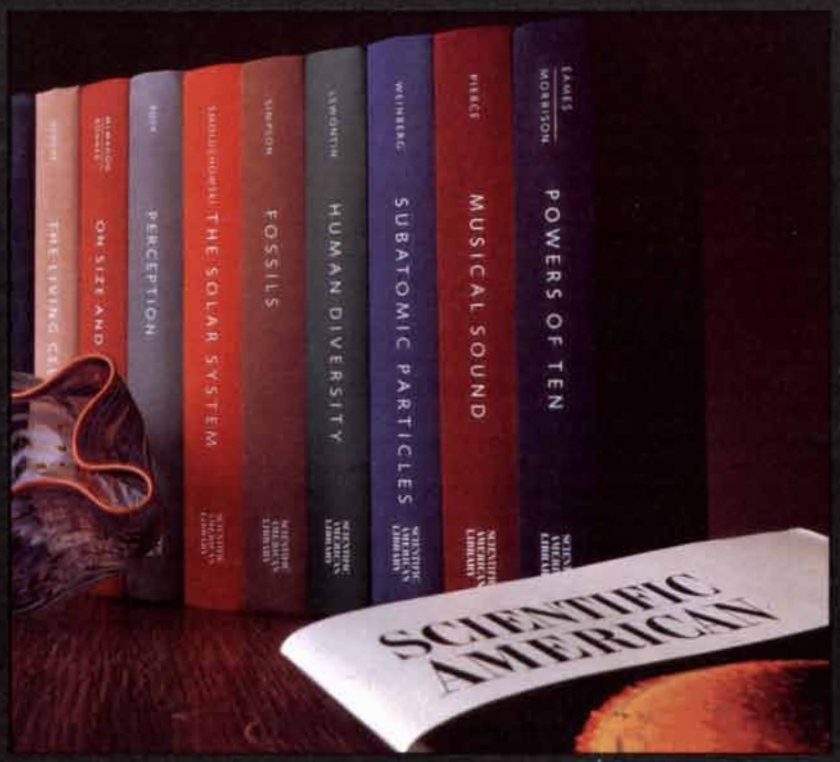

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PERCEPTION

Irvin Rock

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BAN NA DI BURIAL included pots with traces of the foods, usually rice or fish, they once contained and in many instances the severed left foreleg of an ox (*right foreground*). The prominence of the buried individual is indicated by the bronze bracelet on the forearm.

FIVE CLAY VESSELS from the Ban Na Di cemetery, four of them with simple decoration, once held food and drink for the dead. The goblet with a pedestal is a little more than 20 centimeters high. The last of the burials at the Ban Na Di cemetery date to about 400 B.C.

dicates a substantial network of trade. The bracelets were clearly much valued. For example, one marble bracelet had been broken and then carefully joined with bronze wire. The adornments were not exclusively those that could have been worn in adult life: another marble bracelet was so small that it could have been slipped on only in youth.

The decorative objects, including bead necklaces made out of other marine shells, were all from burials concentrated in one part of the Ban Na Di cemetery. Many of the same graves included small clay figurines representing cattle, deer, elephants and in a few instances human beings. One grave, that of a man, held a "herd" of seven cattle figurines.

The abandonment of the cemetery at Ban Na Di after some 1,000 years was not capricious. The years between 500 B.C. and the beginning of the Christian Era were momentous ones in Southeast Asia. Analysis of the pottery found in the layer of debris that accumulated over the deserted burial area indicates that it belongs to a tradition of wares quite distinct from the earlier pottery at the site. Such an abrupt change after 10 centuries of continuity bespeaks the arrival of an alien population.

The final centuries of the first millennium B.C. saw, at least in certain areas of Southeast Asia, a transition from the earlier pattern of small autonomous villages to a social system based on the development of a few large central places and the rise of chiefly authority. The transition was accompanied by (and also doubtless accelerated by) growing contacts with the expanding cultures of India to the west and China to the northeast. The contacts were mainly in the coastal regions; indeed, the earliest eyewitness account of Southeast Asian society is by a Chinese traveler, K'ang T'ai, who described the coastal peoples of the lower Mekong in about A.D. 250. He reported they lived in walled towns that held palaces as well as humbler abodes. Some of the palace tableware was silver, and the authorities taxed transactions in silver, gold, pearls and perfumes.

Archaeological investigations in the lower Red River valley, beginning as long ago as the 1930's, have provided evidence on some of these more complex Southeast Asian societies. At that time a Swedish investigator, Olov R. F. Janse, excavated a number of graves in a rich burial ground on the south bank of a stream near the Red River delta close to the hamlet of Dong S'on. His work yielded, among other artifacts, daggers, body ornaments, drums and ritual urns, all made out of bronze. The Dong S'on assemblage was so rich and so reminiscent of the chiefly hoards then being uncovered in eastern Europe that in order to account for the presence of these bronze artifacts in Viet-

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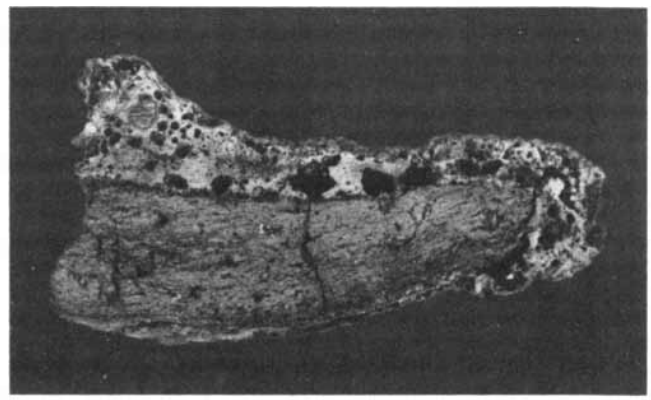
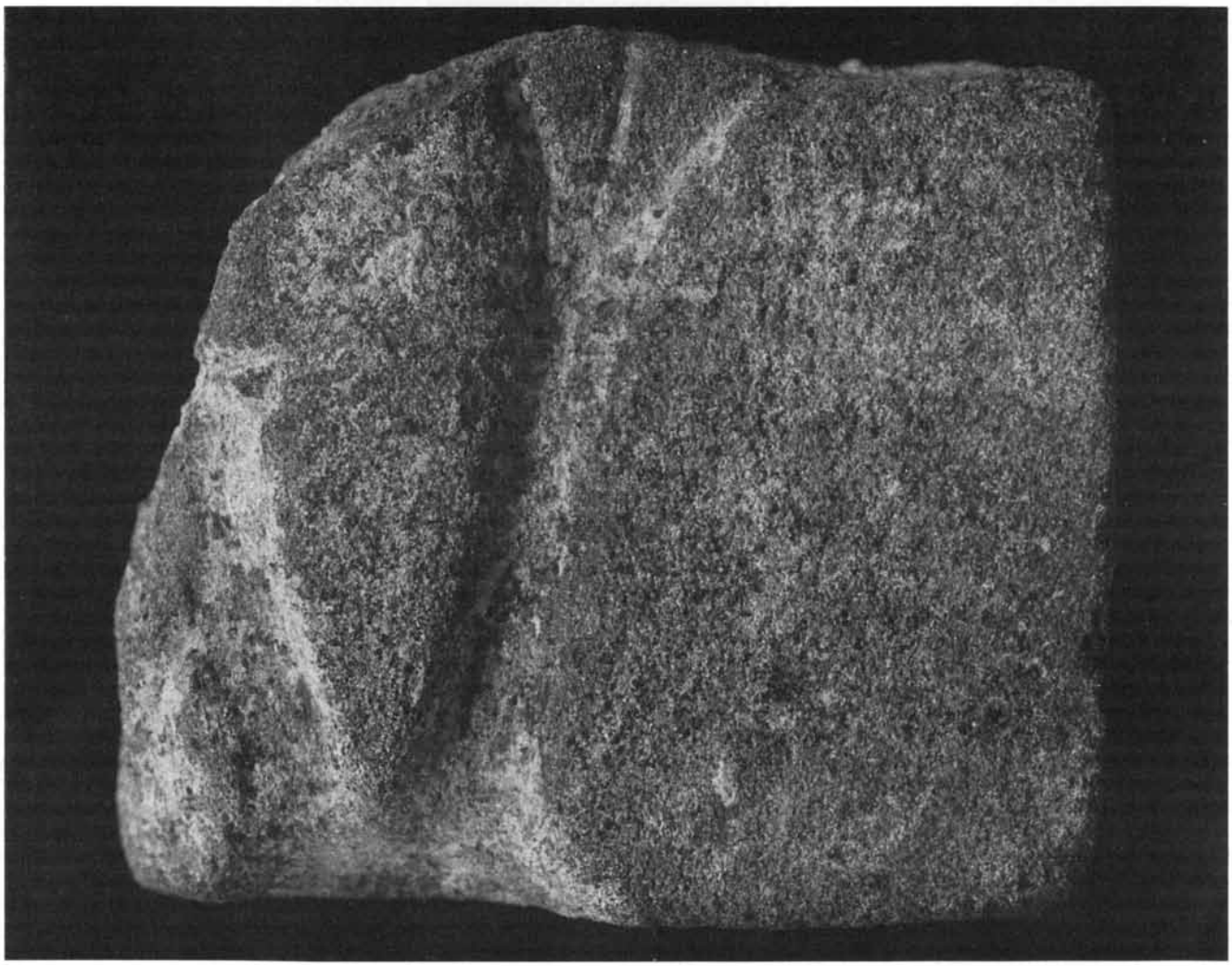
nam serious consideration was given for a time to a hypothetical "Pontic" migration into Southeast Asia.

More recent research on the Dong S'on culture tells a quite different story. Vietnamese archaeologists, who recognize in the Dong S'on people their own direct ancestors, see the site as being peripheral to the main focus of prehistoric sites inland from the Red River delta. Moreover, they can now trace the origin of the culture back to the initial Neolithic settlers of the middle-country Phung Nguyen sites I have mentioned. For example, some of the motifs that appear on the bronze drums found at Dong S'on are also incised on the far earlier pottery of the Phung Nguyen culture.

The decorations of the drums also indicate that the Dong S'on people lived in



CLAY CRUCIBLE at the left was filled with copper and tin by the metalsmiths of Ban Na Di and placed in a clay-lined pit filled with charcoal. The charcoal was then brought with a forced draft of air to a temperature high enough to fuse the two metals into bronze. The crucibles were often used more than once, as the section through a fragment of one of them, at the right, indicates by its layers of dross.



SANDSTONE FRAGMENT is part of a mold used by the Ban Na Di metalsmiths to form a lead replica of a bronze object. When the replica was covered with clay and baked, the lead melted and ran out. The clay mold was then ready to be filled with molten bronze.

a rich, aristocratic warrior society. A common scene shows spearmen with elaborate headdresses, carrying weapons with tasseled shafts. Another scene, running around the drums' entire rim, shows flotillas of war canoes with warriors dressed even more elaborately. Some of the canoes have a raised platform near the stern on which an archer stands. Under the platform is what may be a drum to beat out a rhythm for the oarsmen. Other drum scenes show stilt houses, drummers and more musicians.

It has been estimated that the casting of a single Dong S'on drum called for the smelting of more than seven tons of copper ore. The bronzesmiths made daggers, swords and decorative body plaques for the aristocrat-warriors. They cast bronze receptacles and ladles that probably saw service at the same aristocrats' feasts. Not all their output was devoted to war and display; they also cast scores of heavy socketed bronze plowshares.

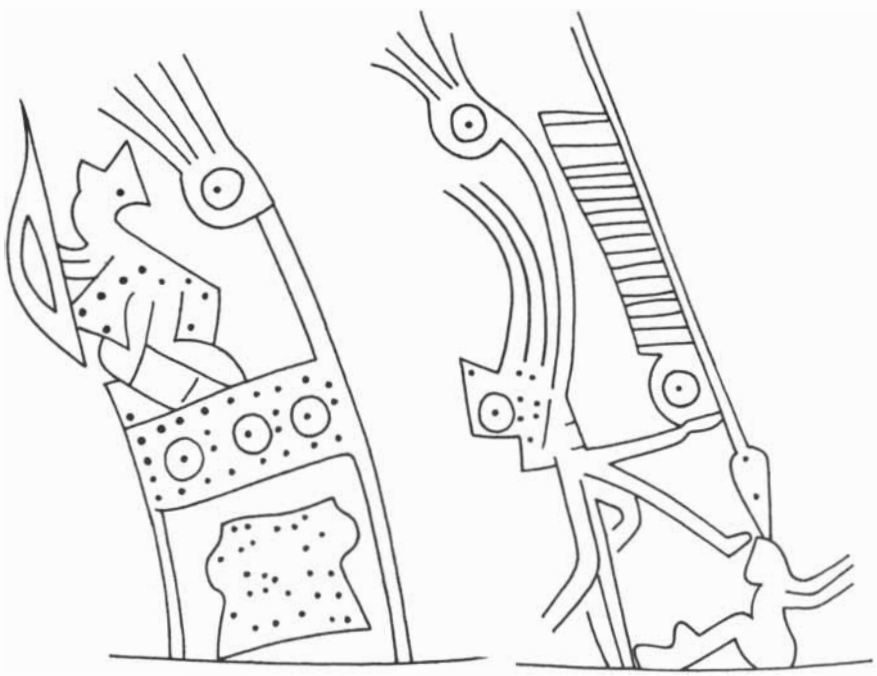
The aristocrats' authority is reflected in their grave goods. For example, at the two Tonkin sites—Chau Can and Viet Khe—Vietnamese archaeologists uncovered coffins shaped to resemble boats. Inside one five-meter coffin at Viet Khe there were more than 100 bronze artifacts, including spearheads, axes, swords and drums.

What was the nature of the Dong S'on economy? Was it sufficiently productive to maintain a full-fledged urbanism? The Vietnam archaeological discoveries suggest that the answer to the second question is yes. The climate of the Red River delta is unique in Southeast Asia. Whereas most of the area has a long dry season, the moist winds of the South China Sea bring low clouds and drizzle to the delta and make it possible to raise two rice crops per year. That the Dong S'on rulers were not overlooking this opportunity is evident both from the large numbers of bronze plowshares found at various Dong S'on sites and from the discovery of different varieties of rice at the sites, indicative of double-cropping.

Some hint of this is found in Chinese accounts of their own advances and withdrawals in the region as the Han dynasty extended its influence in border areas. One such account notes that the Chinese confirmed the local "Lac" chieftains' traditional rights to delta land. Recent archaeological work at a site 15 kilometers northwest of Hanoi provides a more tangible hint: the huge site of Co Loa, long a subject of legend.

All that remains of Co Loa today is three sets of earth ramparts, about six meters high, that stand out boldly above the flat delta landscape. The two outer ramparts are roughly oval and the inner one is rectangular. All three are surrounded by moats fed by a tributary

BRONZE DRUMHEAD, discovered less than a year ago at Co Loa, a city site on a tributary of the Red River, includes in its intricate decoration two bands of figures. The outer band depicts flying birds identified as crane-egrets. The inner band repeats a scene twice. At the bottom of this photograph is a row of four drums of increasing size and, seated above them, four drummers. To their right are two spearmen with elaborate headdresses and tasseled spears, heading a procession of four additional people, possibly musicians. Farther to the right, beyond what may be a dwelling, two individuals are pounding a mortar, presumably husking rice. A structure that seems to be sheltering animals is next; thereafter the same scene is repeated.



DRUM DECORATION representing a Dong S'on war canoe includes the figures shown in this drawing. They are an archer standing on a raised platform (*left*) and a spearman with an elaborate headdress who is cowing a seated prisoner (*right*). Under the platform is a drum.

of the Red River. The area enclosed by the outermost rampart is at least 500 hectares in extent. Pottery of the Dong S'on culture has been uncovered both under and within the two outer ramparts, and a Dong S'on bronze drum was found in the inner enclosure. The drum held within it more than 100 plowshares. Although much more needs to be learned about the settlement patterns and the social organization of the Dong S'on people in general, it is hard not to arrive at the conclusion that Co Loa was an important seat of authority, perhaps even the major Dong S'on administrative center.

Whatever the nature of the indigenous polity in the Red River delta before and at the start of the Christian Era, it was destined to be short-lived. In A.D. 43 the Han general Ma Yüan annexed the region by force and turned it into a border prefecture of the ruling dynasty. Outside the area where the Chinese ruled directly, however, there is mounting archaeological evidence of the development in Southeast Asia first of local chiefdoms and then of states.

A few examples from the Mekong delta will suggest the trend. First, recent aerial photography has revealed a network of ancient canals in the delta. Ground reconnaissance suggests that they date back to the third century A.D., the time when K'ang T'ai visited the region. Second, the ruins of a delta port, Oc Eo, have been known (and looted for gold) for half a century or more, and the French archaeologist Louis Malleret conducted a systematic survey of the 450-hectare area in the 1940's. He found that the site had been a manufacturing center producing, among other goods, beads of glass and amulets of cast tin. Evidence of contacts with neighboring Indian states unearthed by Malleret includes seals engraved with Brahmi script. The site's position in a far-flung network of trade is further attested by his discovery of Roman coins of the second century A.D.

The ruins of the Buddhist-influenced Khmer civilization of Cambodia, such as Angkor, are too familiar to call for comment here. Much less well known, and only becoming better known now, are the numerous moated city sites of the Chao Phraya delta associated with Thailand's first major polity, Dvaravati. One Dvaravati site stands only a few kilometers from the ancient coastline midden of Khok Phanom Di, where our own projected work may reveal whether the hunters and gatherers of 5,000 years ago cultivated rice or only harvested the wild grain. The archaeological sites of the region serve as a reminder that the prehistoric development of rice cultivation was the foundation of both the ancient and the modern states of Southeast Asia.

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THE AMATEUR SCIENTIST

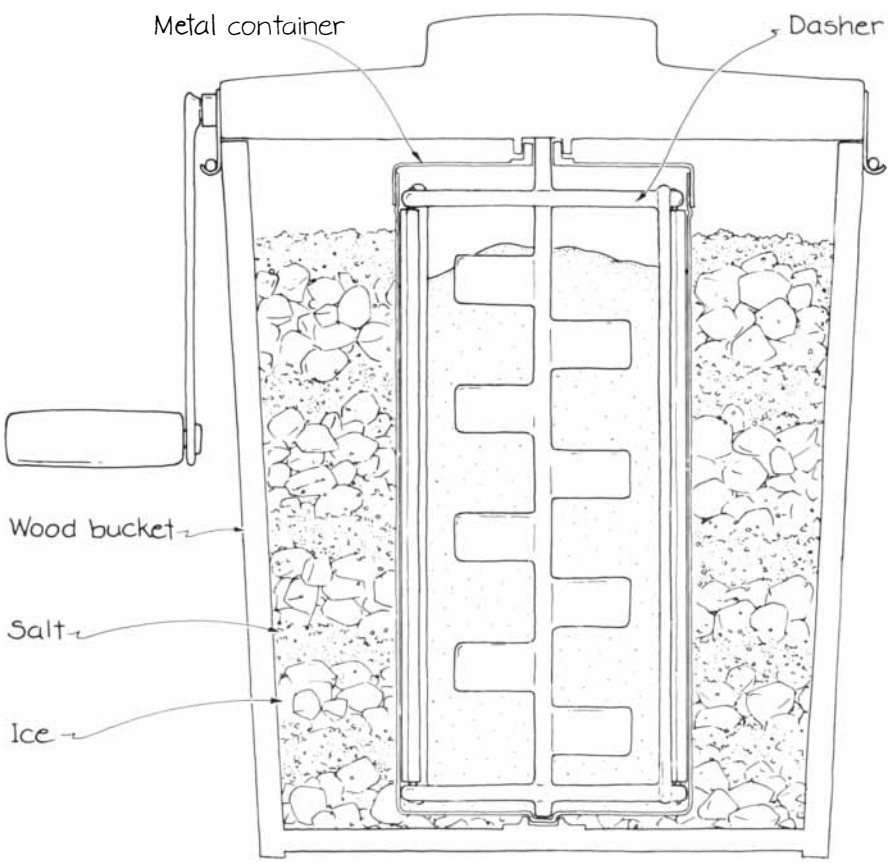
The physics of Grandmother's peerless homemade ice cream

by Jearl Walker

My grandmother makes what I regard as the best ice cream in the world. She relies on an old-fashioned apparatus in which the ingredients that will turn into ice cream are churned by means of a hand crank. During and after the churning the mixture is cooled and hardened by a bath of ice, water and rock salt surrounding the container. The result is a creamy, smooth dessert that one cannot resist.

My grandmother's ice-cream maker has three major parts. A metal container holding the ingredients fits into a much larger wood bucket. A hand-cranked dasher extends into the container. Between the container and the bucket are packed alternating layers of rock salt and crushed ice, roughly four times as much ice as salt. The entire assembly is covered to exclude room heat. My grandmother churns the mixture for about 20 minutes until it becomes quite viscous. Next she repacks the ice and salt, drapes a heavy towel over the apparatus and leaves it for a few hours to freeze hard. The ice cream is then ready for the table.

To investigate the process I have chosen one of my grandmother's recipes for a moderately rich vanilla ice cream. The ingredients for one and a half quarts are listed in the illustration on the opposite page. Warm the cream, stirring in the sugar. Continue to heat and stir the mixture, but do not let it boil. Once it is hot and the sugar has fully dissolved cool it to room temperature and then add the vanilla extract. Pour the mixture into the metal container and put it in the refrigerator for at least an hour. Then mount the container in the bucket and insert the dasher, which you have also cooled in the refrigerator. Pack the ice and salt around the container and begin cranking.



A hand-cranked ice-cream maker

Several aspects of the procedure have intrigued me for many years. I realize the mixture cannot be made into ice cream without ice, but is the salt really needed? Why does my grandmother caution against adding too much salt? Why must the ice be crushed? I know that the bucket should be wood to reduce the absorption of heat from the room, but must the container be metal? Do the ingredients of ice cream serve any purpose other than to make it tasty? I have also wondered (particularly during my long turns at the crank) why the ice cream must be churned. (It is certainly well mixed before it is poured into the container.) Why should the churning rate be increased as the viscosity increases? Finally, why is ice cream ruined if you let it melt and then refreeze it?

My grandmother's explanation of the purpose of the rock salt puzzled me. She maintained the salt was intended to lower the temperature of the ice so that the ice cream would freeze faster. Perhaps she was right, but the idea seemed inconsistent with another common use of salt. When a sidewalk must be cleared of ice, a sprinkling of salt over the ice soon melts it. If salt merely lowers the temperature of ice, how can it melt ice on a sidewalk? Conversely, if the salt merely melts the ice in the ice-cream maker, how can it speed up the freezing of the mixture?

To explore the matter I shall first consider the freezing of tap water (ignoring the possibility of supercooling it, that is, making its temperature drop below the normal freezing point without any freezing). In my simple model of cooling I remove energy (heat) from the kinetic energy of the molecules of the liquid. Since the molecules slow down, the water temperature is lowered. When the freezing point (zero degrees Celsius) is reached, ice begins to form at the surface. The removal of more energy freezes more water but cannot lower the temperature until the water is completely frozen.

Picture an intermediate stage where the water is only partially frozen. If I isolate the mixture to prevent any additional loss of energy, both the temperature and the amount of ice remain constant but the molecules still move, some slowly and others quickly. Along the interface of the liquid and the ice some of the molecules are also constantly chang-

ing states. Some of the molecules in the liquid phase move slowly enough so that when they collide with the ice, they stick, adding to the ice. Simultaneously some of the molecules in the solid phase (the ice) break free to become part of the liquid. When the system is isolated and the temperature is constant, an equilibrium is reached in which the rate of freezing matches the rate of melting at the interface.

An important factor in this model is the energy exchanged in the freezing and the melting. A molecule in the liquid phase that sticks to ice loses energy for two reasons. First, it must slow down, otherwise its kinetic energy would quickly carry it away from the ice. Second, it loses additional energy when it is captured by the electric forces exerted by neighboring molecules in the ice. When a gram of water freezes, the amount of energy lost collectively by the molecules joining the ice is 80 calories.

The converse is true when a molecule leaves the solid phase. It must receive enough energy to escape the forces exerted by the neighboring molecules in the ice and to have a kinetic energy appropriate to being in the liquid phase. For a gram of water to be melted 80 calories must be supplied in order to free the molecules from the ice. Hence when equilibrium is reached in ice water, the amount of energy given up by the molecules joining the ice matches the energy taken up by the molecules leaving the ice. There is no net exchange of energy across the ice-liquid interface.

Suppose I remove a small amount of energy from a system that is in equilibrium with half of its water frozen. The average speed of the molecules in the liquid phase decreases and the freezing rate increases as the now slower molecules begin to stick to the ice. In this period the freezing rate is higher than the melting rate and there is a net release of energy.

The energy does not disappear. It shows up (through collisions) in the kinetic energy of the molecules that are still in the liquid phase. Before long enough energy is added to them so that fewer of them stick to the ice. Once again the freezing and melting rates match and equilibrium is restored.

Every time I remove a small amount of energy from the system I upset the equilibrium. Molecules slowed by the removal join the ice. After each removal the system reestablishes equilibrium. Eventually if enough energy is removed, all the molecules are in the solid phase. Even in the solid phase, however, the molecules are in motion: they vibrate around their positions in the crystal lattice of the ice. Now each removal of energy slows the vibration, and again the temperature begins to drop.

Reconsider the equilibrium where half of the water is frozen. If you add salt to the liquid, the equilibrium is momentarily destroyed. Although a water molecule is electrically neutral, it has a strong electric dipole field because its atoms are arrayed in the form of a *V*. In a simple model of the molecule the oxygen atom, which is at the point of the *V*, pulls the electrons of the hydrogen atoms toward the point. This movement separates the centers of positive and negative charge in the molecule. The oxygen end can thus be regarded as more negative than the hydrogen ends.

The electric field of the water molecules breaks up the salt crystals into positive sodium ions and negative chloride ions. Each ion is surrounded by a loose cluster of water molecules. Around a hydrated sodium ion (Na^+) the water molecules on the average present their oxygen ends to the ion. Around a negative chloride ion (Cl^-) the water molecules on the average present their hydrogen ends. At least some of the water molecules in these clusters are held so tightly that they cannot freeze.

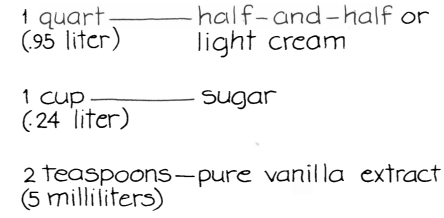
Now some of the collisions at the ice-liquid interface involve clusters, which cannot stick to the ice. Hence the equilibrium at the interface is destroyed by adding salt because the clusters diminish the frequency with which water molecules enter the ice phase. The frequency with which they leave the ice is unchanged, so that the ice begins to melt.

The melting accomplishes two things, both of which increase the freezing rate so that it again matches the melting rate. The water that melts dilutes the salty solution, increasing the probability that a collision at the interface will be by a water molecule rather than by a hydrated ion. Melting also lowers the temperature of the system because each molecule freed from the ice must be supplied with energy by molecules in the liquid. As the liquid loses energy it cools.

When salt is sprinkled over ice on a sidewalk, the system of salty ice water is different because it is not isolated. Although the water might at first cool as it supplies energy for melting, the sidewalk and the surrounding air quickly make up the lost energy. The temperature stays constant while the ice melts.

Often the purpose of the salt is stated in terms of the freezing point of the ice water. When salt is added, the freezing point of water is lowered from its normal level of zero degrees C. The freezing process then extends over a broad range of temperatures. In the upper illustration on page 153 the temperature of salty ice water is plotted as a function of the liquid's salinity, measured in parts per 1,000, specifically the number of grams of salt in 1,000 grams of liquid. The curve represents the equilibrium values at which the rates of freezing and melting are balanced.

To understand the freezing of salty



Ingredients for vanilla ice cream

water you might begin with the liquid at low salinity. As you remove energy from the mixture by cooling it the temperature eventually goes below zero degrees C., and yet the mixture does not freeze. The freezing point of the mixture is lower by several degrees than the freezing point of fresh water. The addition of the salt is said to have depressed the freezing point.

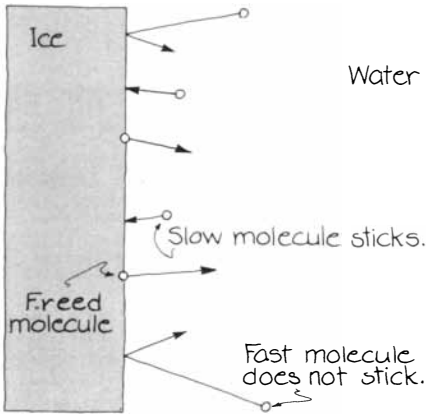
Every time energy is removed from the system the freezing rate becomes higher than the melting rate and part of the water freezes until the rates are rebalanced. Since the amount of liquid water decreases, the salinity increases. As you continue to cool the system and upset its equilibrium, it reestablishes the equilibrium and moves down the curve.

Eventually the system reaches a state called the eutectic point. Further cooling then solidifies the entire system into ice and hydrated sodium chloride. The temperature of the eutectic point depends on the type of salt. For sodium chloride it is about -21.1 degrees C., with a salinity of 233 parts per 1,000. A solution of calcium chloride has a eutectic point with a temperature of -55 degrees, which is why calcium chloride is much better than sodium chloride for melting ice on a sidewalk in cold weather. The calcium chloride depresses the freezing point of water more than sodium chloride does.

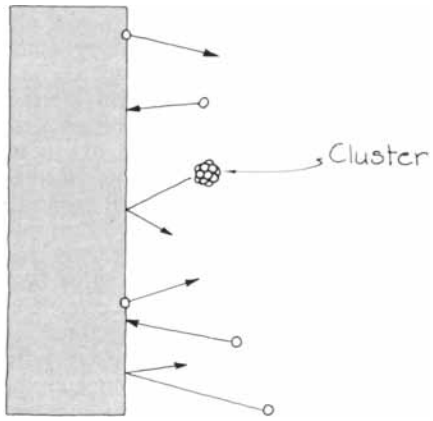
The same type of graph serves as a guide for adding sodium chloride to the ice in an ice-cream maker. Suppose you have added a small amount of salt to the ice so that the salty ice water is approximately in equilibrium at a temperature not far below zero degrees C. This point is labeled *A* in the lower illustration on page 153. Since the temperature is not very low, the ice-cream mixture freezes slowly. Tired of cranking, you decide to put more salt in the ice.

The additional salt momentarily destroys the equilibrium in the system because the new supply of sodium and chloride ions binds more of the water molecules into clusters. Since the freezing rate decreases, part of the ice melts as the system heads back toward equilibrium. And since the system is almost isolated, the energy required for melting must come from the kinetic energy of the water molecules. They slow down, and so the temperature decreases.

Eventually enough of the ice melts



Equilibrium in ice water



Equilibrium in salty ice water

so that the freezing rate again matches the melting rate. Equilibrium is reestablished, but at a lower point on the curve. In spite of the melting of some of the ice the salinity is now higher than it was at the outset because of the additional salt. More important, the temperature is now lower because energy was removed in the melting process.

In an ice-cream maker the salty ice water is not an isolated system. Energy leaks at a low rate through the wood walls. Even more energy comes from the mixture that is to be frozen. Still, the point is that the addition of salt to the ice water drives the temperature down by melting some of the ice. The cold liquid bath can then remove energy from the container of ingredients. The salty ice water remains cold even though the ice-cream mixture continues to supply energy. The container should be metal so that energy can be conducted into the bath to freeze the mixture in a reasonable amount of time.

I checked the ability of salt to decrease the temperature of ice water by salting ice water in a Thermos bottle. I monitored the temperature with an unmounted type *K* thermocouple connected to a thermocouple thermometer bought from the Cole-Parmer Instrument Company (7425 North Oak Park Avenue, Chicago, Ill. 60648). As I added more salt, ice melted and the temperature dropped until it was −15 degrees C. There it stopped, presumably because heat was leaking into the bottle.

Is ordinary ice suitable for freezing an ice-cream mixture? It is if enough of it makes good contact with the container. Ice cubes do not pack well. Chopped ice makes more contact but still not enough to keep the churning time reasonably short. Indeed, the churning time might be so long that butter separates from the ice-cream mixture and no ice cream results. Far better contact is made when the container is surrounded by a bath of ice water. Without salt in the bath, however, the ice water can be no colder than zero degrees C.

With salt in the bath the container will be surrounded by a liquid that is colder than zero degrees C. The more salt, the lower the temperature. My grandmother cautions, however, that one should not add too much salt or the ice cream will be ruined. Salt and ice should be in a ratio of about 1 : 4. More salt creates too low a temperature in the ice-water bath. Since the difference in temperature between the ice water and the ice-cream mixture is then greater, heat is conducted through the wall of the container at a higher rate. Heat is not conducted through the ice-cream mixture as quickly. Hence the layer of mixture adjacent to the wall cools and freezes rapidly whereas mixture farther from the wall does not.

Churning the mixture helps to prevent the early freezing of the outside layer. Still, if the ice-water bath is cold enough, early freezing may set in. The dasher is then difficult to turn even though the center of the ice cream is not yet viscous. The person cranking, misled by the resistance of the dasher to turning, concludes that the mixture needs no more churning and allows it to sit for a while. As a result ice crystals grow, giving the product a hard, grainy texture.

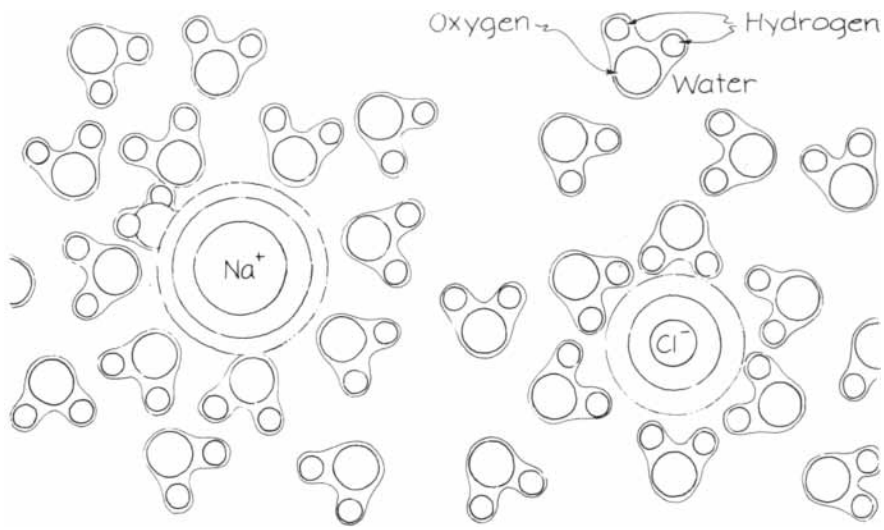
The initial mixture of ingredients is enough to fill about 70 percent of the container. As you churn the mixture it expands enough to fill the container, partly because water expands when it freezes. Much more of the expansion, however, is due to the air beaten into the mixture by the churning.

When I first begin to churn, I turn the handle slowly because the viscosity of the mixture is too low to trap air bubbles. Vigorous turning would be wasted effort. Besides, I do not want to churn butter out of the cream. When the solution has cooled and become thicker, I must turn the handle faster to work air bubbles into the mixture. They are trapped in the fluid by the viscosity and the freezing. Their effect is to lighten the ice cream, which otherwise would be as heavy as ice.

The ice-cream mixture is prepared hot so that the sugar and other ingredients dissolve and mix thoroughly. Obviously if it is still hot when you put it in the ice-cream maker, the bath of salty ice water must remove a great deal more heat. That is why you should cool the mixture, the dasher and the container in the refrigerator for an hour or even longer.

When an ice-cream mixture is frozen without churning, it is grainy. The difference in the final texture comes from the growth of ice crystals in the mixture. Suppose the mixture is cooled and frozen slowly in a freezer. A few tiny ice crystals appear. They grow as more water separates from the mixture to crystallize at those sites. When the ice cream is completely frozen, it is full of large ice crystals.

When an ice-cream mixture is churned as it freezes, the crystals are much smaller. The motion of the churning disrupts the process of crystallization, and the initial nucleating sites no



Hydrated ions of sodium (Na^+) *and chlorine* (Cl^-)

longer dominate it. Instead many more sites have a chance to initiate crystals. The mixture freezes into a great many small crystals rather than a few large ones. The result is smooth ice cream.

Churning also prevents the formation of large ice crystals in another way. It coats the newly formed crystals with some of the cream in the solution. It is then difficult for more water to reach the crystal surfaces. Crystal growth is retarded and new crystal sites can appear. Milk, eggs, honey and gelatin also serve to retard crystal growth.

If you must make ice cream in your freezer compartment, occasionally beat it with an electric mixer or blender. This procedure breaks up some of the ice crystals and coats them with the cream. In addition it beats air bubbles into the mixture.

I did several simple experiments with ice cream. I prepared a batch according to my grandmother's recipe and divided it between two bowls, which I covered with aluminum foil and put in my freezer. The freezer stays at approximately −12 degrees C., which is cold enough to freeze ice cream. As ice began to form along the edge of the mixtures, I removed one batch and beat it for several minutes in a mixer at low speed. Then I put it back in the freezer.

Several hours later both mixtures were well frozen. The one that had been beaten had many small air bubbles frozen in place. Removing small samples with a spoon, I could see ice crystals a few millimeters long, large enough for me to feel them when I put the ice cream in my mouth. I could both feel and hear the crystals crunch between my teeth.

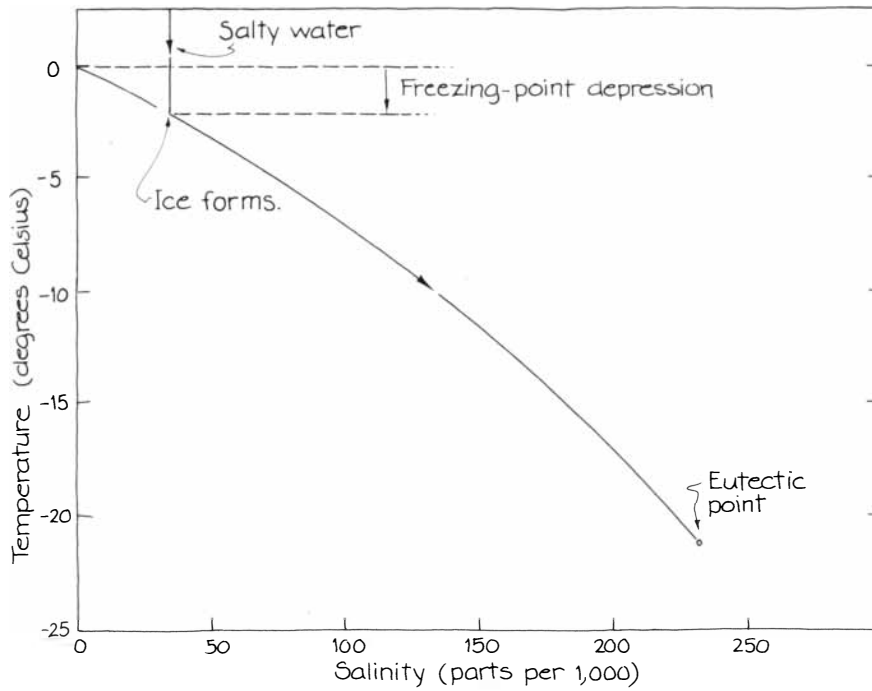
The mixture that had not been beaten was hard with ice. It was also dense because there were no air bubbles in it. The edge of the spoon made noise as it broke through the ice. When I put a sample in my mouth, some of the pieces of ice were too big to crunch readily. Eating the stuff was like chewing small ice cubes. The same kind of failed ice cream results when I melt a good sample and then refreeze it.

I compared both mixtures with some I had made from the same recipe and churned. One sample was churned in an apparatus identical with my grandmother's except that it was driven electrically. The other sample was prepared in an electric ice-cream maker lent to me by Peter Renz, an editor at W. H. Freeman and Company. His machine fits into a freezer compartment with its electric cord extending out to a wall plug. (The rubber gasket on the freezer door fits snugly around the cord.) It has a small fan that blows air past the ice cream container to speed the freezing.

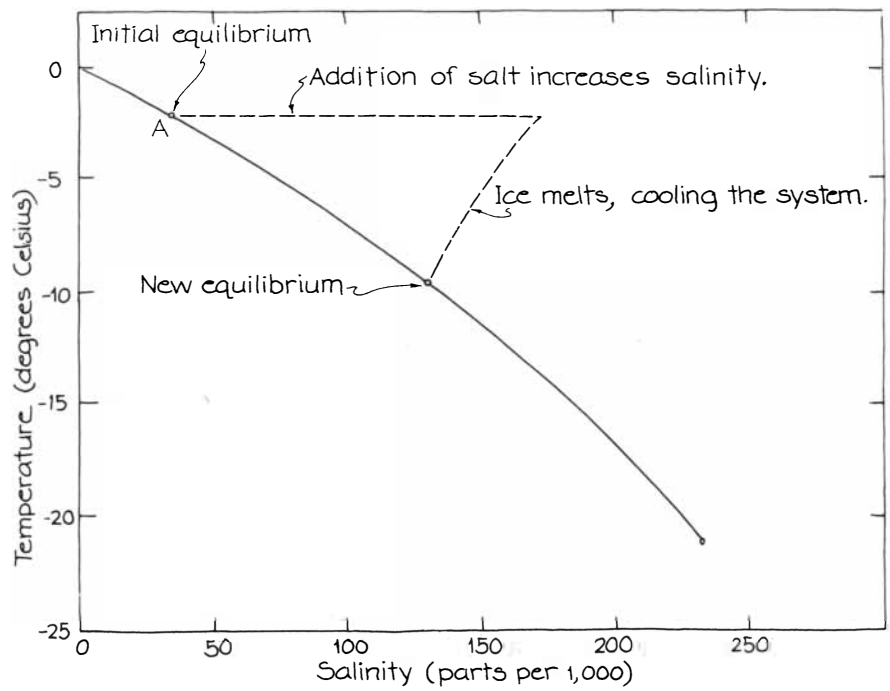
Whereas my machine with salted ice takes about 20 minutes of churning to make ice cream, the machine with a blower takes more than an hour. Both machines make smooth, light ice cream. I can see ice crystals and air bubbles only when I examine samples under a magnifying lens.

Several desserts similar to ice cream could be investigated. Sherbet, which usually includes a citrus juice and tiny bits of rind, lacks the cream of ice cream. It requires churning or beating because the growth of ice crystals can make it grainy and hard. The problem can be worse because many sherbets lack an ingredient that would coat the ice crystals and retard their growth.

A sorbet is prepared in a similar way except that a fruit is pureed and then blended into a sugar syrup. A granita is almost the same except that it is not churned or beaten, resulting in deliberately large ice crystals. While the mixture is freezing you should stir it periodically with a fork to leave it sharp with crystals but not lumpy with little ice cubes.



Conditions as salty ice water freezes



How the addition of salt intensifies cooling

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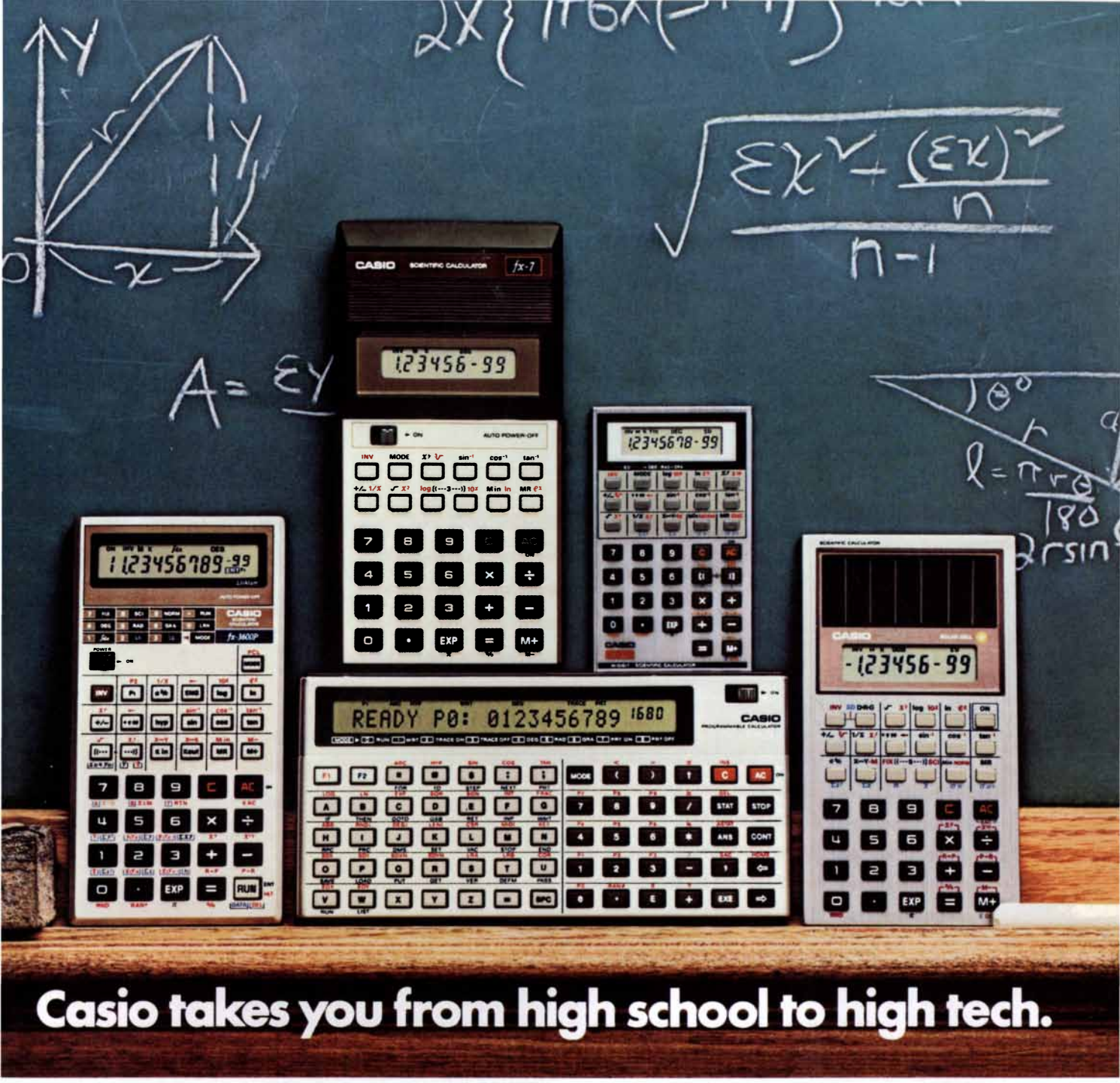

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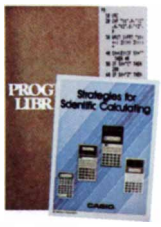

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