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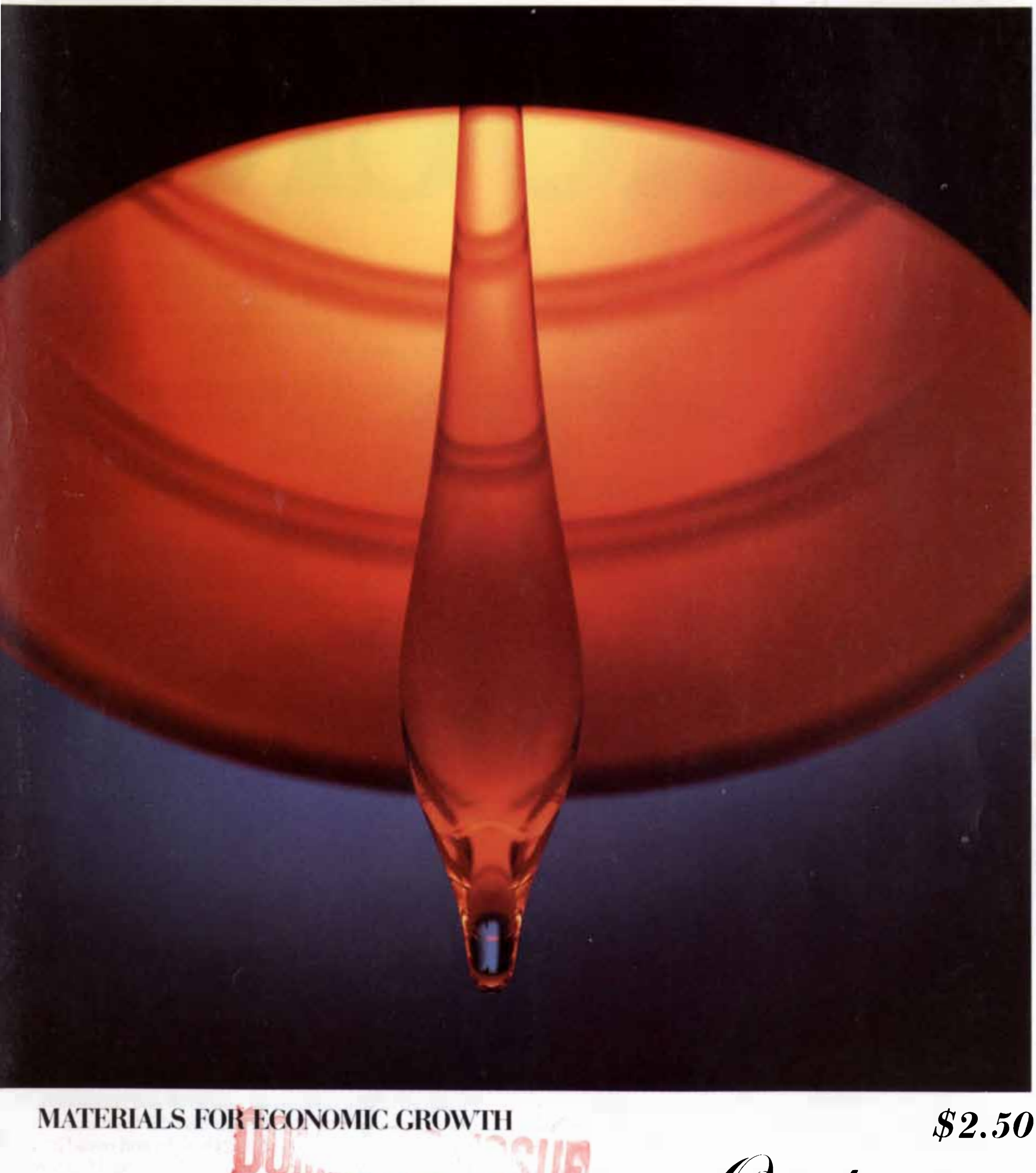


MATERIALS FOR ECONOMIC GROWTH

$2.50

October 1986

WHY GMC TRUCK IS SAYING...

"IT'S NO

A TRUCK A

A GMC truck is still a truck as defined by law. But that's about it. In all other respects, a GMC truck of today has about as much in common with its early forebears as a 747 has with a World War I biplane.

The key word here is "just." "Just a truck" implies mere adequacy. Functionality and nothing more. That's the way trucks were. That's not the way GMC trucks are.

TOO CIVILIZED TO BE JUST A TRUCK.

Time was when trucks had to hide out in the alleys and byways of the country making pickups and deliveries. You just couldn't take them anywhere.

That's not the case today. A GMC truck is bred for better things. It will still pridefully perform the work of our nation. but it will do so with a great sense of style.

Light-duty GMC trucks come with the well-mannered niceties of a car. They offer air conditioning and stereo and plush seating and power this and power that.

What's more, there's something about the lively "lemme at it" look of a truck that hints of an active and probably interesting lifestyle.

So, today, you will see GMC trucks perched proudly in the darndest places. Like the front of Restaurant Chez Posh. And the driveway of the rather impressive split-level at the end of your block.

Trucks are the hottest-selling vehicles in the country today. And at GMC Truck, business has never been better. GMC trucks appeal to tasteful buyers seeking quality and integrity.

WHEN PEOPLE WANT WHAT YOU WORK ON, YOU WORK A LITTLE HARDER.

There was a time not so long ago, when a job putting together trucks was probably pretty unexciting. That's when trucks were just trucks.

Today, as the vehicles of preference for so many interesting buyers, trucks border on the glamorous. We can sense that feeling filtering from the showroom to the assembly line.

From the design engineers to the people who assemble to the final inspection teams, there's an infectious new sense of pride and purpose. Everyone knows they're doing something important: producing trucks that more and more people want today.

SNEAK PREVIEW, COMING SOON.

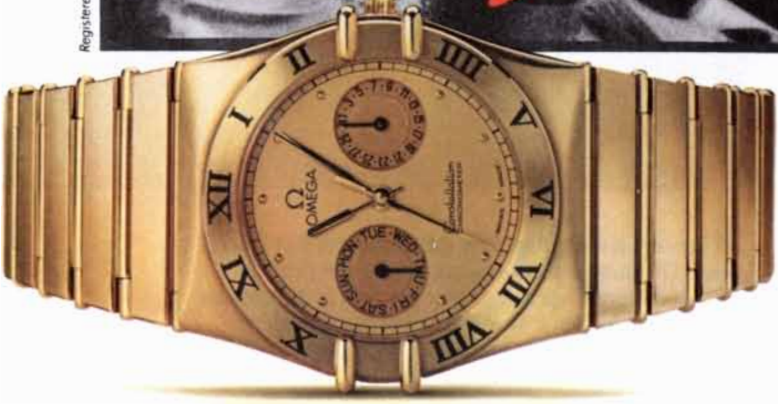
GMC Truck today is a beehive of activity. We bring you heavy-duty Generals and medium-duty Top Kicks and buses for schools. We offer Jimmys and Safari Vans and small space-age pickups. All crafted with such enthusiasm, we're saying they're "not just trucks anymore."

In that same soaring spirit, we will soon launch our most exciting vehicle concept of all. We went back to our roots. To that classic of classics — the most trucklike of trucks — the American full-size pickup.

We stared at that pickup and pondered and ruminated over it. As good as it was, we wondered if we could make it even better. Then we re-thought and re-did it. And it will be better. It will serve ranchers and farmers and foremen as never before.

Like our other vehicles, this new pickup will not just be four wheels surrounded by a spartan paint job. The


Significant Moments
Registered Model


OMEGA

Established 1845 **SCIENTIFIC AMERICAN** October 1986 Volume 255 Number 4

ARTICLES

DEPARTMENTS

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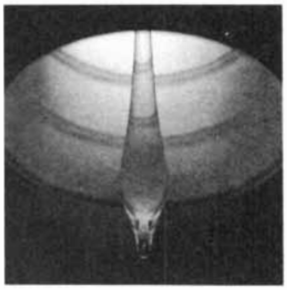

THE COVER

The photograph on the cover symbolizes the theme of this issue of SCIENTIFIC AMERICAN: how powerful economic incentives have led to the development of new materials and the industrial technology needed to produce them. In the photograph a gob of molten glass forms at the end of a blank of optical-waveguide glass at the Corning Glass Works manufacturing plant in Wilmington, N.C. As the gob falls to the bottom of a draw tower, its weight pulls the glass like a strand of taffy into a thin fiber about .1 millimeter in diameter. The elaborate technology devised for making optical fibers has been driven by the enormous demand for the transmission of information.

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LETTERS

To the Editors:

"Beyond the Era of Materials," by Eric D. Larson, Marc H. Ross and Robert H. Williams [SCIENTIFIC AMERICAN, June], was interesting because it showed specifically that the role of materials is a changing factor in our technology. The thrust of the article, however, and the title in particular give the unwarranted impression that materials have become passé. The authors use kilograms per capita and kilograms per unit of gross national product as criteria for discerning the change. Are these the right criteria? Should the judgment not be made on the basis of value, or of technology?

As a case in point, the authors cite the substitution of materials. They are correct in saying that high-strength steel and stainless steel have now replaced 14 percent of the carbon steel and cast iron in an automobile, compared with 5 percent in 1975. Each kilogram of the new materials eliminates 1.3 kilograms of the earlier products. The authors fail to note, however, that the value of the new materials and the technology they represent are increased by factors of from two to 10 depending on the nature of the substitution. Other new materials, such as fiber-reinforced plastics, that are substituted for traditional materials also carry to the final product an increased emphasis on materials development, materials production and value.

For some reason the authors believe the roles of processing and design are replacing the role of materials. In reality these functions are all blending. The significance of each function, including materials, has become paramount. One need only look at semiconductor technology or the emerging optical-fiber industry to recognize this synergy. It is true that the number of kilograms of glass fibers, of silicon and of other new materials per capita will not be overwhelming, but the value of technologically critical materials cannot be underestimated. Given the foreseeable potential, one could conclude that we are *entering* the Era of Materials.

LAWRENCE H. VAN VLACK

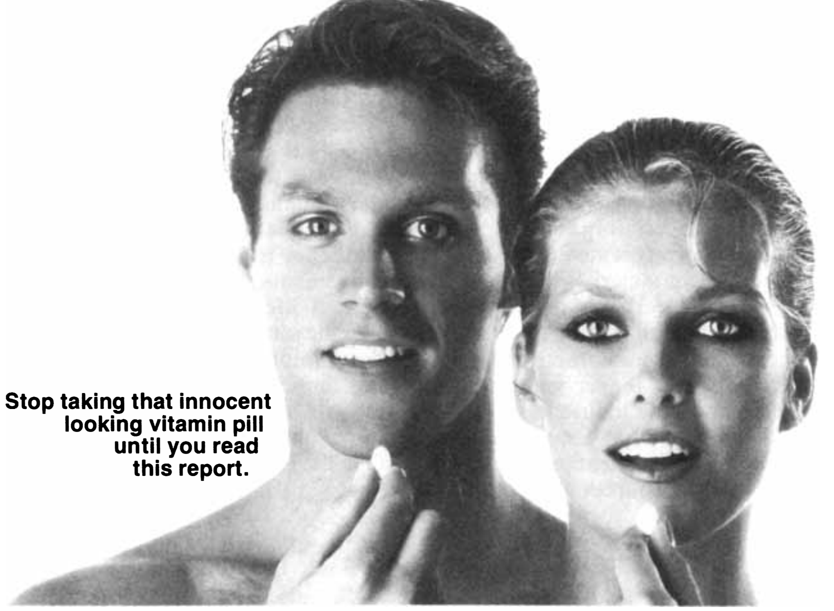
Department of Materials
and Metallurgical Engineering
University of Michigan
Ann Arbor

To the Editors:

What's in a name? That which we

Stop Taking Vitamins

If you think the vitamins you are now taking are doing you any good, wait until you hear the latest news on why they may not.



Stop taking that innocent looking vitamin pill until you read this report.

By Joseph Sugarman

This may come as a shock. But according to the latest research, those vitamins that you take every day may be doing you absolutely no good. For example.

FACT: Vitamins should be taken after a meal—never before. The body must first have protein, fats, or carbohydrates in the digestive tract to properly break down the vitamins for proper absorption.

FACT: Your body has a need for a natural vitamin balance. Too much of one vitamin may cause another vitamin to be less effective. For example, vitamin A should be taken with Vitamin E but excessive iron should not.

FACT: If you take too much calcium, you may deplete the magnesium in your system. And you need magnesium to convert food into energy.

FACT: Some vitamins are best taken in the morning and others at night. For example, the trace element chromium helps break down the sugar in your food which in turn creates energy—perfect to start the day. But at night you should take Calcium which has a relaxing effect—perfect for the evening.

FACT: Athletes or people who exercise a great deal need vitamins more than people who don't exercise. Vitamins are depleted at a much faster rate during exercise than during any other period of time.

But there was a series of other facts that surprised me too. For example, despite everything I've just mentioned on the care in taking vitamins, there are those people who absolutely need vitamins because of the mental or physical activity that they undergo. People on a diet, under stress, those who smoke, women who take contraceptives and even those who take medication—all rob their bodies of some of the essential vitamins and minerals that they need to help combat the various habits or conditions they are under.

And with proper vitamins in the proper balance and at the proper times, you will have more energy and vitality. Little changes may take place. Your nails may become stronger, your hair may become thicker and your skin may be more elastic which will keep you younger-looking longer.

DOCTORS HAD IDEA

About two years ago a group of doctors had an idea. They realized that many people were taking vitamins and not really noticing any difference in their health. They also realized that, based on the latest nutritional findings, the vitamins people were taking may not have been doing them any good. So they formed a group of advisors consisting of nutritionists, dieticians, dermatologists, biochemists and physicians, and they worked on the development of a vitamin program that incorporated all of the latest information on vitamins, minerals, nutrition, food processing—even stress research. They realized that vitamins were a two-edged sword. They could either help you or hurt you.

They then took all this information and developed the most effective combination of vitamins and minerals, formulated four tablets—one for the morning and one for the evening—and one for men and one for women and then started a test program that lasted over two years. The results speak for themselves.

It was perfect for weight loss programs and it was perfect for people under stress. It helped many increase their energy levels. Smokers benefited. Some under medication benefited. And before long the company that had developed the program became the fastest growing vitamin company in the United States. And no wonder.

SEVERAL BENEFITS

With the proper vitamin and mineral balance, taken in the right quantity in the right combination and at the right time, several obvious benefits occur. First, you may develop a better mental outlook because you've got the energy and the zest to accomplish more. As a result of the trace elements copper, zinc and manganese, your body is helped to make its natural anti-aging enzymes that keep you fit. Improvements in your vitality translate into everything from better job performance to a more fulfilling sex life.

JS&A has been selected by the vitamin company to introduce their medically formulated vitamin program. Every two months we send you a two month's supply of 120 fitness tablets—one to be taken after breakfast and one after dinner.

During the first two months, you will have ample opportunity to notice the difference in your energy level, your mental attitude and your overall stamina. You should notice little things too, like the strength of your fingernails, your thicker hair. Your complexion may even take on a glow. Some of you may notice all of these changes and others may notice just a few. But you should notice a change.

If for any reason, you do not notice a change, no problem. Just pick up your phone, and tell us not to send you any more vitamins. And if you ask for a refund, you won't even have to send the empty bottle back. It's yours free for just giving us the opportunity to introduce our vitamins. However, if you indeed do notice a difference (which we are confident you will), you'll automatically receive a two-month's supply every eight weeks.

ONE MORE INCENTIVE

I'm also going to give you one more incentive just to let me prove to you how powerful this program really is. I will send you a bonus gift of a fitness bag with your first order. This beautiful bag will hold all your fitness gear and it's great too for short vacation trips. It's a $20 value but it's yours free for just trying the vitamins. Even if you decide not to continue, you keep the fitness bag. I am so convinced that you will feel and see a difference when you take these vitamins that I am willing to gamble on it with this unusual offer.

Vitamins indeed are important. And with today's research and new nutrition technology, you have a greater chance to achieve the fitness and health levels that may have eluded you with the typical store vitamins or the poor advice we may get in health food stores or from friends. Here is a safe, risk-free way to get one of the best vitamin programs in the country, formulated by a physician, with the right combination of vitamins, minerals and trace elements, in a convenient program that assures you of delivery every two months. I personally take and highly recommend them. Order your trial quantity, today.

To order, credit card holders call toll free and ask for product number (shown in parentheses) or send a check and include $2.50 for delivery.

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Women's Vitamins (1156SA)........	**$24**

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IL residents add 7% sales tax. ©JS&A Group, Inc.,1986 call "beyond the era of materials" by any other name would tell the same story. The particular points cogently made by Professor Van Vlack are points made in our article. The thrust of his letter is certainly valid. New materials are being created with remarkably useful characteristics, and the science and engineering of materials may be more important than ever. At the same time, because the tonnage of materials is no longer growing with the economy, the industrialized countries have arrived at a watershed that has important implications for energy and mineral resources and for industrial policy.

ERIC D. LARSON

MARC H. ROSS

ROBERT H. WILLIAMS

To the Editors:

Thank you for Ralph Norman Haber's excellent article, "Flight Simulation" [SCIENTIFIC AMERICAN, July]. As a systems engineer and commercial pilot, I found it lucid and informative. The only nit I pick is the choice of words indicating that the 1979 O'Hare DC-10 accident happened when the plane "lost an engine." The phrase is commonly used to mean power failure. In the event mentioned the machinery itself tore loose, taking part of the wing with it, and bored a hole in the pavement.

A more serious concern has to do with the physical motion of simulators. I suspect the feature is a pointless and potentially dangerous fad. Acceleration vectors in a properly flown aircraft always point along a line between the pilot's head and his toes ("up" or "down" in the moving reference frame). That's what the ball on the instrument panel is for: to maintain coordinated flight. Aircraft do not turn by yawing, even in military maneuvers. A tight, high-speed change of course in a fighter is made by what we commercial folk teasingly call the "bank and yank" method—the pilot stands the plane on one wing and hauls back on the stick. The acceleration is vertical with respect to the airframe.

Simulator motion may be dangerous because it can lead a student to rely on inner-ear cues. As Haber said, they "are compelling." Since the subjective forces in coordinated flight are always up or down (any lateral vectors simply indicate skidding or slipping), one cannot—indeed, one must not—rely on such cues to deduce aircraft attitude. Every year a few non-instrument-rated pilots die when they fly into clouds, lose visual references, rely on "seat of the pants" judgment and fly a perfectly coordinated, ball-centered, ever tightening spiral into the ground.

Instrument-rated pilots, on the other hand, are trained to ignore subjective movements, both in a simulator and in real life, no matter how compelling they may be to the untrained. For those pilots the added cost of providing motion cues is pointless. Consequently simulator motion would seem to accomplish little more than to inflate the device's face value and price.

FRANK SWEET

Jacksonville, Fla.

To the Editors:

Providing motion information in flight simulators has been from the very beginning an expensive but inconclusive enterprise. Pressures toward realism have demanded that a proper sense of motion be available to a pilot flying a simulator. This has led to more sophisticated motion platforms, which have evolved from relatively simple piston-driven systems to ones in which the entire cockpit is moved around within a hangar-size room.

In arguing that these efforts are misplaced Sweet advances two points: simulators do not provide the pilot with the proper information about the motion of the plane, and that information is in any case not useful.

With respect to the generation of motion information, all current and even planned simulators are inadequate. The accelerations produced in any reasonable simulator are of low amplitude—less than 2 *g*'s (two times the force of gravity) at best—and can be sustained for no more than fractions of a second. In contrast, in a fighter aircraft a tightly banked turn can increase the forces experienced by a pilot from 1 *g* to 7 *g*'s in less than half a second, and the forces remain at that level until the pilot rolls out of the turn 15 or more seconds later. Consequently there is always a discrepancy between the information available about motion in real aircraft and that in simulators. The discrepancy is smaller in simulations of aircraft that do not maneuver rapidly, but it remains.

Because of the inadequate fidelity of motion information in all flight simulators, most of them are operated today without a motion platform or with the system turned off. Virtually all the research done on the simulation of motion has concluded that the performance of pilots flying simulators is not enhanced by motion information.

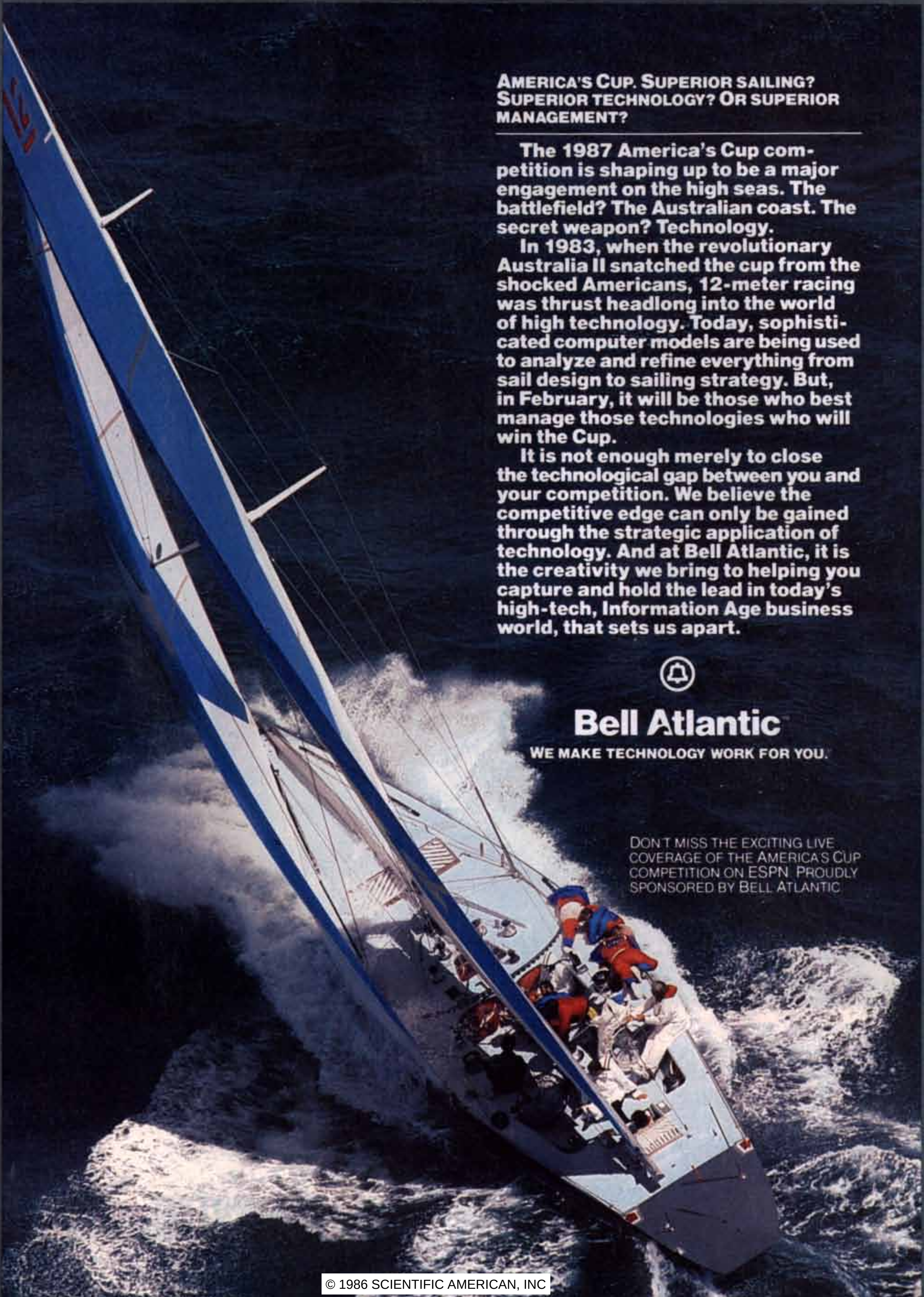
One symptom of the inconsistency of the motion information available in a simulator and the sensations of actual flight is the "simulator motion sickness" many pilots experience. This nausea is thought to result from the mismatch between the rich visual information telling the pilot about his movements through space and the inadequate and inaccurate information about movements imparted by the motion platform to the pilot's vestibular nervous system. Turning the motion platform off does not remove the mismatch but merely changes it: the pilot now sees himself moving but feels no corresponding accelerations. As a result simulator sickness is likely to remain with us.

Sweet's second point is more fundamental. He argues that pilots should not attend to motion information delivered to the vestibular system, even in actual flight, since it can mislead them. The reasons for this possibility are well known. The vestibular sensory organs adapt very readily, so that during sustained *g* forces they process information about the onset of those forces but then respond relatively little to their continuation. When pilots begin a turn, they can "feel" its onset as motion, but if the turn continues, their vestibular system stops responding, almost as if the turn had ended. If pilots can see the ground, they can tell that the plane is still turning and ignore the inaccurate vestibular information suggesting the turn has ended.

In clouds or at night over unlighted terrain, however, pilots lack visual information, and if they rely on their vestibular system, they may indeed misperceive their actual motion. After turning for a few seconds they sense that the turn has ended prematurely, and so they want to increase the rate of turn. This inappropriate response can lead to a spiraling descent into the ground, as Sweet notes. Pilots have to be trained to follow their instruments for information about their attitude in relation to the ground.

Sweet concludes by suggesting simulator motion accomplishes little that is relevant to flight training. That is undoubtedly true, at least in today's simulators. But the more important conclusion concerns our visual sense: flying is a visual task, and little useful information comes to the pilot from any of his other sensory systems, including his vestibular system. Research must therefore aim for an understanding of how perception works in the environment of flight and include investigations of the role of visual components in flight simulation.

RALPH NORMAN HABER

WE BELIEVE THAT THE GENIUS OF THE FUTURE LIES NOT IN TECHNOLOGY ALONE, BUT IN THE ABILITY TO MANAGE IT.

AMERICA'S CUP. SUPERIOR SAILING? SUPERIOR TECHNOLOGY? OR SUPERIOR MANAGEMENT?

The 1987 America's Cup competition is shaping up to be a major engagement on the high seas. The battlefield? The Australian coast. The secret weapon? Technology.

In 1983, when the revolutionary Australia II snatched the cup from the shocked Americans, 12-meter racing was thrust headlong into the world of high technology. Today, sophisticated computer models are being used to analyze and refine everything from sail design to sailing strategy. But, in February, it will be those who best manage those technologies who will win the Cup.

It is not enough merely to close the technological gap between you and your competition. We believe the competitive edge can only be gained through the strategic application of technology. And at Bell Atlantic, it is the creativity we bring to helping you capture and hold the lead in today's high-tech, Information Age business world, that sets us apart.

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50 AND 100 YEARS AGO

SCIENTIFIC AMERICAN

OCTOBER, 1936: "Population trends indicate that we shall become a nation of old people within the present century. Fewer children are being born, while the average life span is being raised. Advances in the science and practice of surgery and medicine, improved sanitation, labor-saving inventions and a higher standard of living have added a decade to the average life since the turn of the century. Thirty-six years ago the average length of life for white males was 48 years and for white females 51 years; today the figures are respectively 59 and 63. The figures show too that the number of babies dying in the first year of life has been cut in half. Approximately 6,500,000 persons are now over 65. This group will be trebled in 50 years."

"Every now and then someone recalls the widespread early predictions that radio would prove of tremendous educational value. Instead of 'educational,' let us use 'enlightenment.' On such a basis, radio broadcasting has done so much good for all the people that we may overlook its more obvious faults. Amazement has of late often been expressed at the conversation of the man-in-the-street on economics and sociology, politics and international affairs, war and peace and the pros and cons of almost every conceivable subject. Over the radio he has heard the voices of political candidates, of kings and dictators, of opera stars and commentators on everything under the sun. He has heard leaders in every walk of life discuss and argue the subjects closest to their hearts. There is your education! It is enlightenment and culture."

"Airline passenger fares average six cents per mile. Until June 1 this compared favorably with rail plus Pullman fares. After that date the cost of rail plus Pullman was reduced about 20 percent. The higher cost of air tickets is more than balanced by the time saved, the reduced expense for meals while traveling and so on. Hence the opinion of a well-informed group of aviation men was that air travel is worth some differential and that the operators who are just coming out of the red should keep to the present scale of prices for some little time."

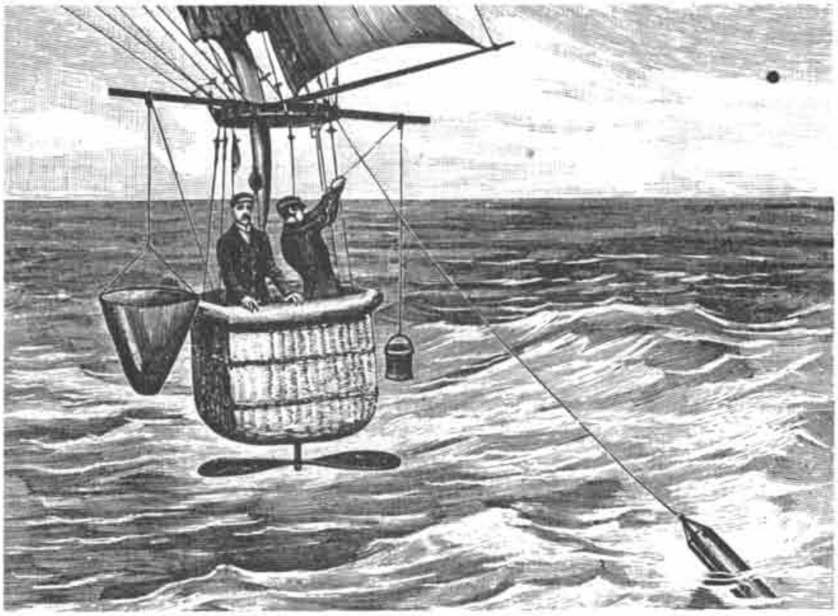
"One of the most perplexing of astronomical problems is the origin of our solar system. It presents a large central body surrounded by numerous small ones, all revolving about it in nearly circular orbits close to the same plane and in the direction of rotation of the central body; and this property is repeated four times in the satellite system of the planets from Mars to Jupiter. This cannot be an accident."

SCIENTIFIC AMERICAN

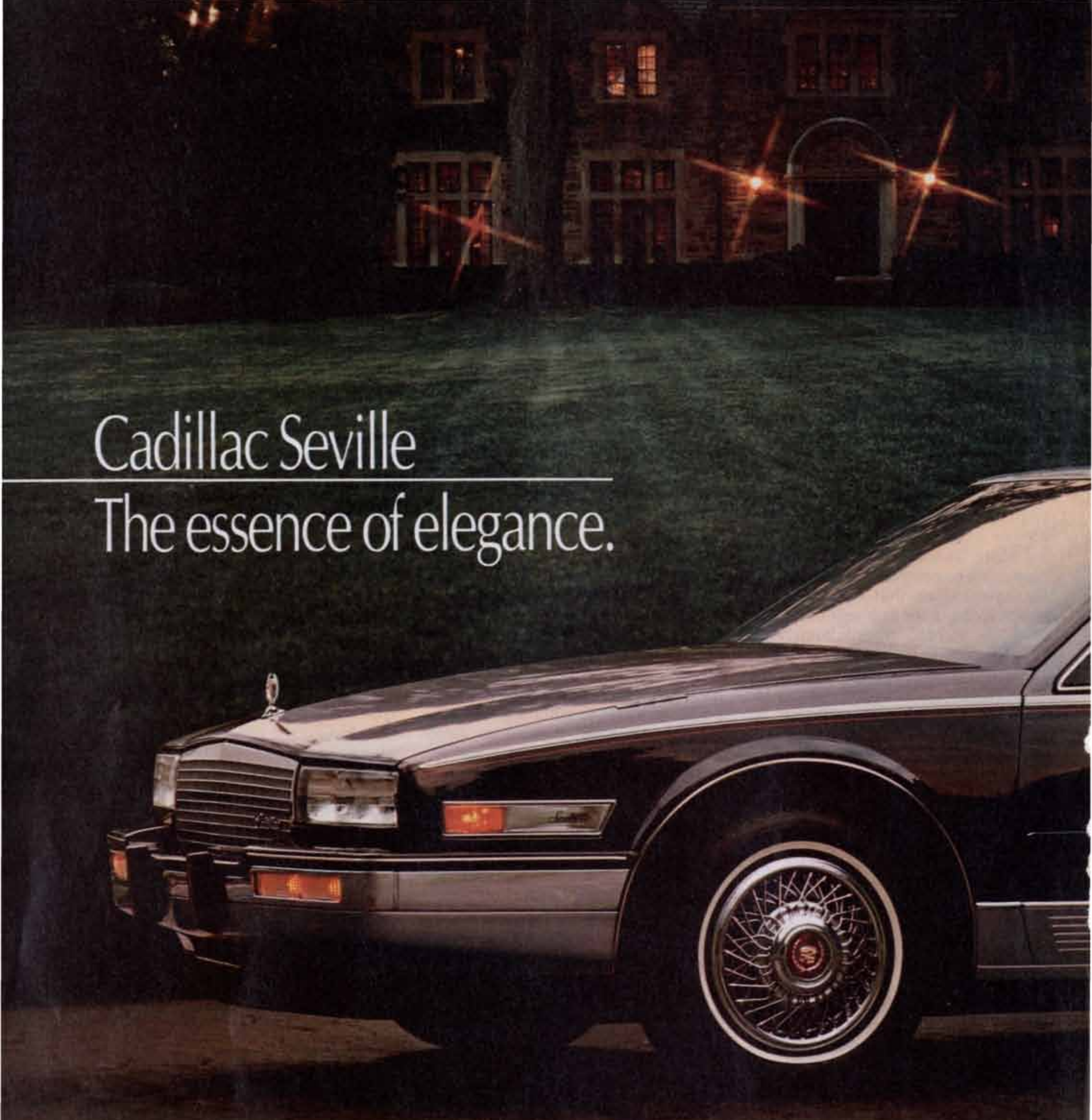
OCTOBER, 1886: "Although much is being accomplished in long distance telephony at various parts of the country, it has not yet reached a point as to efficiency that may be regarded as wholly satisfactory, nor has it yet proved itself formidable in competition with the telegraph. Long distance telephony may be compared with fast time on the railway. It is possible on the railway to make a mile a minute, and still better time is sometimes made both here and abroad, but it has been found undesirable, on economic grounds, to run faster than forty miles the hour. And so in telephony 100 miles or thereabout seem to be the paying limit at present."

"An agreeable illustration of the capacity of the feminine mind to grapple with the abstractions of science was afforded in the recent annual meeting of the American Science Association, whose proceedings were illuminated by the personal participation of several lady members. A paper by Mrs. Nuthall Pinart was read, in the section of anthropology, containing some analyses of Mexican inscriptions. In the section of chemistry, Mrs. Helen C. De S. Abbott read a paper on the proximate composition of a bark from Honduras that contains a new camphor and a yellow coloring matter. In the section of economic science a paper was read, written by Mrs. John Lucas, on silk culture."

"A young and already celebrated aeronaut, Mr. F. Lhoste, has twice in the past made a trip through the air from Boulogne to England, but these interesting expeditions could have been successful only through his alternate utilization of superposed currents. These circumstances put it into his head to cross the English Channel, from Cherbourg as a starting point, through a S.S.W. wind, which is one that is well established and frequent in these quarters. He and his companion, Mr. J. Mangot, succeeded in their first ascent. Among the means employed by these explorers for traveling in a balloon over the sea, we consider as very important the use of a float for converting the balloon into a captive one, and the use of a cone anchor, permitting of the reception of water hoisted up from the ocean with a pail, since the sun at daybreak tends to cause the balloon to rise. With these several methods of anchoring one's self to the sea and taking in ballast, it is not impossible to undertake long balloon trips over the ocean."



Directing a balloon at sea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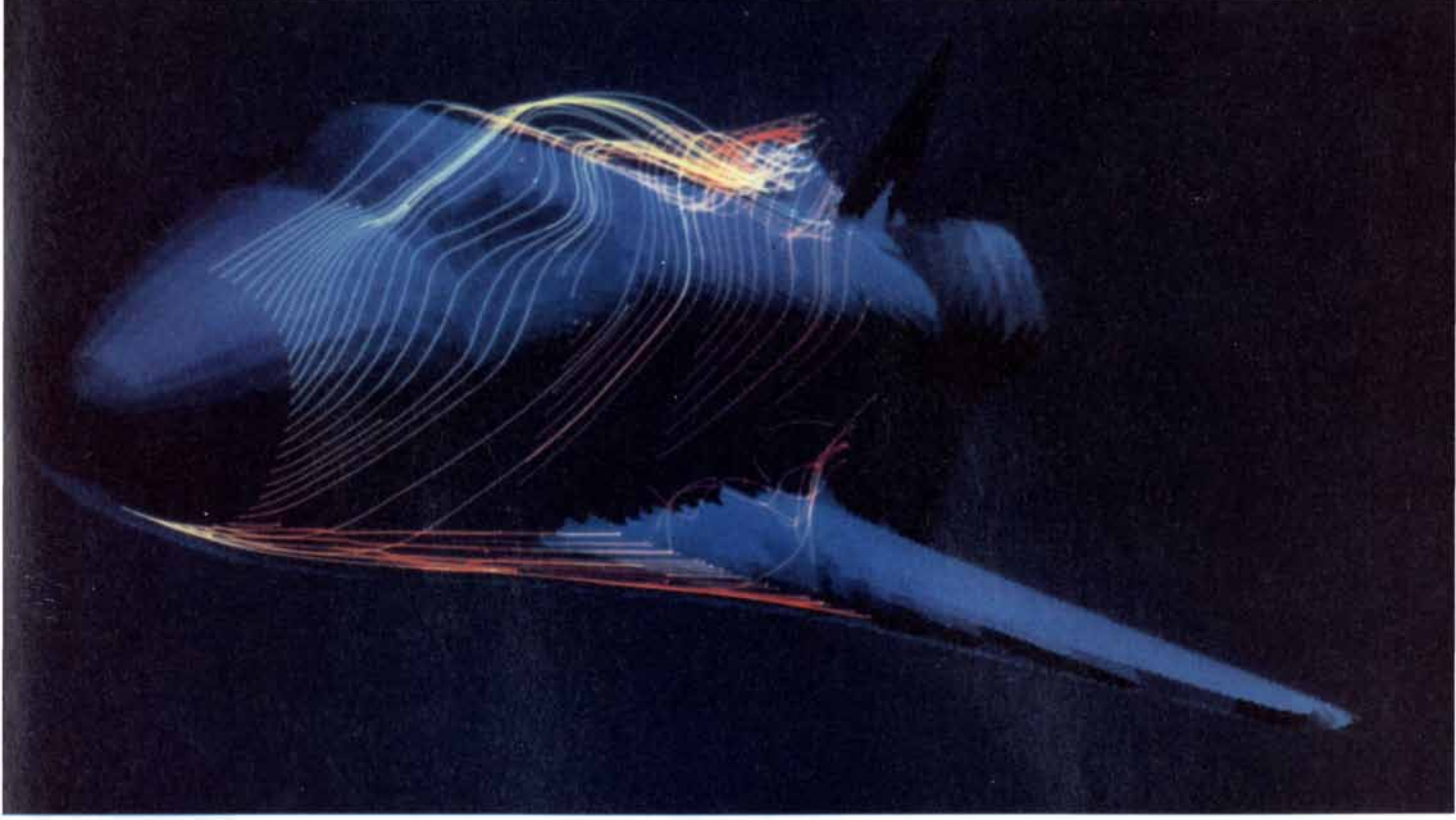
JOHN S. MAYO ("Materials for Information and Communication") is executive vice-president for network systems at the AT&T Bell Laboratories. During his career at Bell Laboratories he has had an important role in the development of a number of technologies, including the TELSTAR satellite, video teleconferencing, ocean sonar, digital switching systems, integrated circuits and photonic devices. Currently he oversees research in electronics, transmission and switching systems and network planning. Mayo received his degrees in electrical engineering, including a Ph.D., from North Carolina State University.

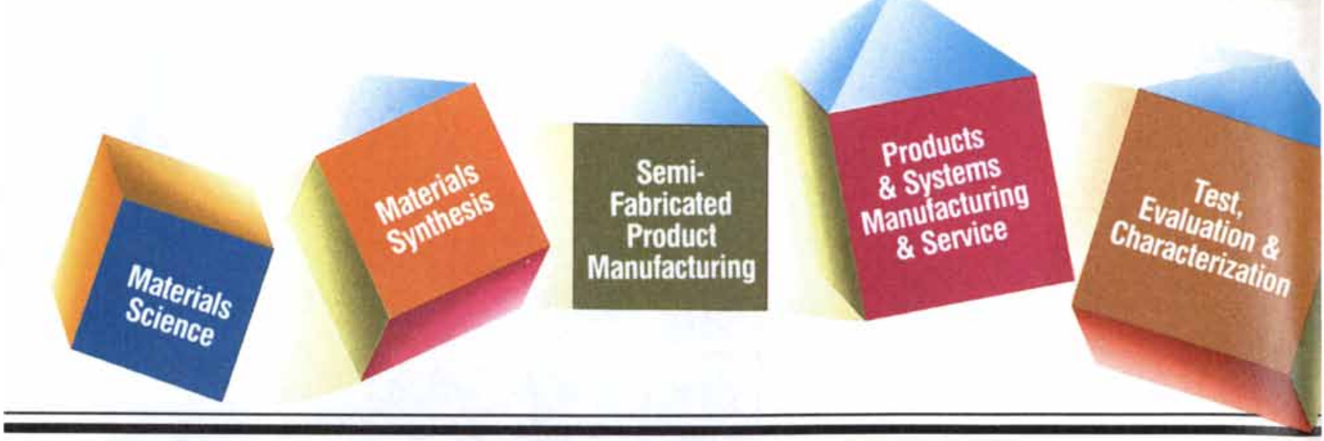
MORRIS A. STEINBERG ("Materials for Aerospace") retired at the end of last year from the Lockheed Corporation, where he had worked in research for 27 years. In his last position as vice-president for science he was responsible for promoting the application of new technologies in commercial products. He is now a consultant in aerospace engineering as well as adjunct professor of materials science and engineering at the University of California at Los Angeles. Steinberg got his B.S. from the Massachusetts Institute of Technology in 1942, and after three years as an Air Force captain in the European theater he returned to get an M.S. and a D.Sc. in metallurgy.

W. DALE COMPTON and NORMAN A. GJOSTEIN ("Materials for Ground Transportation") have both worked for the Ford Motor Company. Compton, after 16 years at Ford, recently accepted a position as senior fellow at the National Academy of Engineering. While at Ford he served as director of the chemical and physical sciences laboratory and vice-president for research. Earlier he was professor of physics at the University of Illinois, where he received his Ph.D. in 1955. Gjostein is director of Ford's systems research laboratory. He has been with Ford since 1960, when he joined the company as a research scientist. He has held several positions, including one in which he assisted Compton in planning and coordinating advanced engineering and research programs. He has a B.S. and an M.S. from the Illinois Institute of Technology and an M.S. and a Ph.D. from Carnegie-Mellon University.

RICHARD S. CLAASSEN and LOUIS A. GIRIFALCO ("Materials for Energy Utilization") are respectively vice-president of the Sandia National Laboratories in Livermore, Calif., and university professor of materials science at the University of Pennsylvania. After getting a B.S. in physics from Cornell University in 1944, Claassen took a job as a research assistant on the Manhattan Project in New York. He received a Ph.D. in physics in 1950 from the University of Minnesota and joined Sandia in Albuquerque soon afterward. In 1982 he moved to Livermore. Girifalco has taught at Pennsylvania since 1961; he has also held various administrative positions, including that of vice-provost for research. His M.S. and Ph.D. from the University of Cincinnati are in solid-state physics, but in recent years his interest has turned to the economic importance of energy.

ROBERT A. FULLER and JONATHAN J. ROSEN ("Materials for Medicine") work in the corporate office of science and technology at Johnson & Johnson, Fuller as vice-president for science and engineering and Rosen as director of scientific affairs. Fuller, a native of Canada, has been associated with various national and foreign divisions of Johnson & Johnson. His first job was with the Canadian affiliate, which he joined in 1959 after receiving his Ph.D. in biochemistry from the University of Minnesota. He took his present position in 1981. Rosen got his Ph.D. in biomaterials science from Case Western Reserve University in 1974. After staying at Case Western



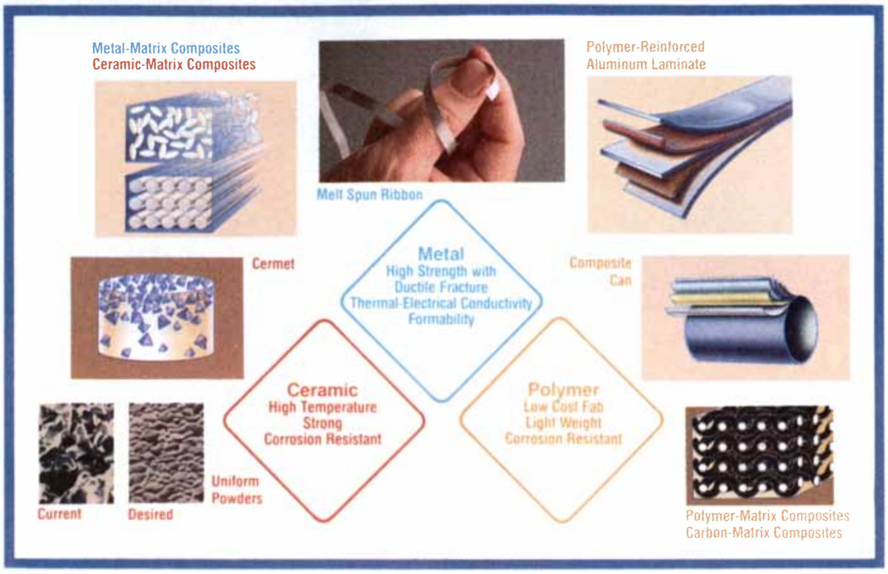


Integrating fundamental materials understanding with advanced manufacturing technologies and product design and performance is elemental for success in the marketplace of the 1990's and beyond.

Alcoa's expanding research and development portfolio reflects this broad, interdisciplinary approach.

by Dr. Peter R. Bridenbaugh
Vice President, Research & Development

Alcoa's Universe of Advanced Materials



The materials industry today is in the midst of a technological explosion that is creating major economic opportunities for those companies willing to commit scientific and engineering resources to capture them.

These opportunities are driven by two factors...market demand and scientific understanding. Transportation, aerospace, defense, packaging, construction and the energy-generating industries are already designing extremely sophisticated and efficient products that will be made from materials that today are laboratory curiosities. The rapid advancement in understanding the fundamental relationship between materials and their structures in the last decade is perfectly timed for application in the development of a new body of knowledge concerning the design, characterization, processing, testing and manufacturing of a whole new generation of advanced materials.

Excellent examples of "product-pull" are emerging from the aerospace industry. The transatmospheric vehicle and manned space stations will demand materials that can only come from the combination of metals, ceramics and polymers in highly-engineered composite and laminate systems.

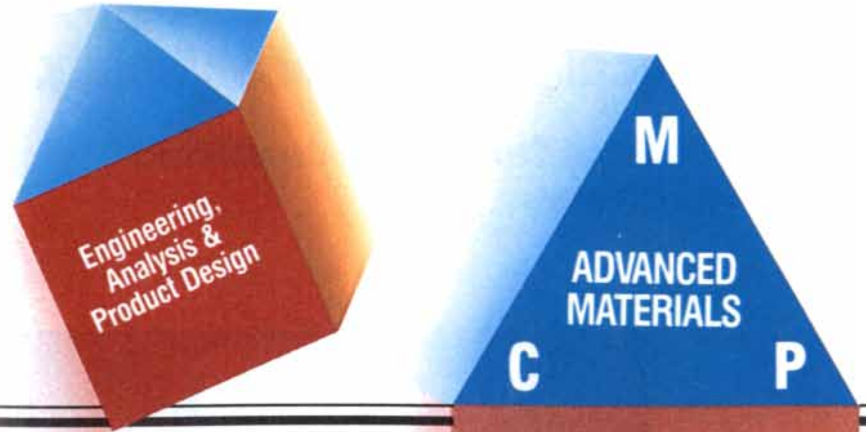
The T.A.V. will fly at speeds somewhere between Mach 15 and Mach 25 and at altitudes around 200,000 feet. Its scram jet engines will operate at temperatures as high as 2200°C. Alcoa considers the best path to building this engine to be through the discovery, development, processing and non-destructive characterization of high-temperature, tough and strong fiber-reinforced ceramic-matrix or carbon-matrix composites.

The matrix and reinforcing materials that appear most promising to us at this time include aluminum oxide, mullite, silicon carbides and silicon nitrides. Plasma-produced titanium diboride and boron carbide also look promising in whisker or continuous filament form as reinforcing materials. Several approaches to ceramic whisker production are under intense development in Alcoa Laboratories.

Vital to the construction of a manned space station is a material with an extended service life in space. Atomic oxygen, a predominant species in low-earth orbit, appears to oxidize organic-based materials and polymer matrices. To counteract this phenomenon requires the development of a laminate material combining the strength and lightness of carbon-based composites with a thin protective coating of metal, metal oxide or glass resin.

This year Alcoa Laboratories initiated a specific program in ceramic-matrix-composites. Our program is based upon three years of research that has resulted in a fundamental understanding of the production of uniform ceramic powders. This understanding, and the resultant capability to produce a broadening array of both oxide and non-oxide powders possessing unique properties, puts Alcoa in a strong position to develop and produce tomorrow's highly-engineered ceramics.

In the shorter-term, the next 5 to 10 years, there also appears to be adequate room for growth in more conventional aluminum applications. In the coming decade, Alcoa will introduce new products that will significantly influence the materials marketplace...including aluminum- and magnesium-lithium alloys, lighter-weight, easy-opening beer, soft drink and food cans, components for aluminum-intensive vehicles constructed around a space-frame concept, unitized bridge deck systems, memory disks and advanced packaging systems for both foods and beverages...to name a few.



ALCOA

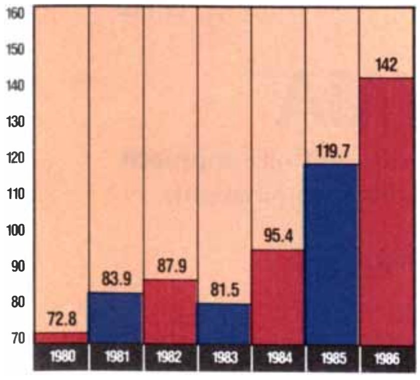
Our success, in ceramics, polymers, metal-based materials and their laminate and composite combinations, will depend upon the ability of our technical communities to integrate their knowledge of materials structures with their increasing understanding of process control, flexible manufacturing and product design and performance.

Our scientists must continue to push forward quantitative understanding of the effect of processes on product properties and characteristics. We must develop quantitative relationships between processing, microstructure, final properties and performance as the foundation for process models. Such models are prerequisites for consistent and reliable control of manufacturing.

Alcoa Laboratories is pursuing two approaches to process modeling. The first is based on first principles. The second is heuristic modeling based on qualitative judgments captured in expert systems. These two modeling approaches will be brought together and applied to the implementation of computer integrated manufacturing.

In the fundamental mathematical area, we are constructing physics-based models describing plastic flow, microstructural changes and failure mechanisms of materials under homogeneous or microscopically uniform conditions. Changes in shape and material structure resulting from the application of a known stress and spatially uniform temperature history are determined and expressed mathematically in constitutive equations. The equations are then incorporated not only into models of material processes but also into models of the performance of products made from those materials.

Research and Development Expenditures (millions of dollars)



Our scientists and engineers are developing such models for the behavior of ingot-based and rapidly solidified aluminum alloys and for porous metals. We are also extending this work to the behavior of other metals, ceramics, polymers, laminates and composites.

In process and product design modeling—building models of the behavior of materials in processes and applications—the basic understanding of fundamental material behavior captured in the constitutive equations is combined with basic physical laws, such as equations of motion and mass conservation, to develop complete mathematical models of process/product behavior.

In most areas of manufacturing, however, there are large gaps in precise quantitative knowledge needed to develop the models necessary for integrated control. In today's world, manufacturing control requires critical analytical thought by experienced personnel possessing deep process and materials understanding. We believe that here is where the powerful diagnostic tools of artificial intelligence will play a major role.

Knowledge-based expert systems will help identify and characterize process anomalies and will eventually combine quantitative process/metal structure understanding with experiential/heuristic process knowledge. Once the combined algorithmic-heuristic models have been developed, they can be used to identify fundamental relationships among key parameters. This combination will ultimately allow us to gain control of both process and product.

The demand for advanced materials produced from computer-integrated manufacturing techniques will be driven primarily by industrialized, economically and technically advanced societies. These societies, however, will not be alone in their need for structural materials.

The world's emerging nations, capitalizing on their raw material, energy and labor resources and guided by their social and economic priorities, will gradually become the world's mining, refining and smelting resources. In these nations, where a viable aluminum industry is in place, aluminum will be used in much the same way that today's industrialized nations used it to develop their commercial and manufacturing infrastructures. The emerging nations, however, will demand the most advanced technologies available and will be unforgiving of either process or product anomalies.

By the end of this decade and beginning of the next, there will be two distinct materials markets. One will be focused on advanced, highly-engineered laminate and composite materials systems designed to meet extremely complex product design specifications. This market will be centered in the industrialized nations. The second marketplace will be focused on the production of primary products and on traditional applications, such as cable, commercial and residential building and industrial infrastructure development. It will be centered in emerging nations.

One constant, however, will characterize both markets. They will be led by integrated, technically-dominant companies who have successfully harnessed the forces of the scientific and engineering revolution taking place in structural materials today.

Alcoa intends to be in the vanguard of these companies.

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Aluminum Company of America
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Pittsburgh, PA 15219

or to:

Dr. Peter R. Bridenbaugh
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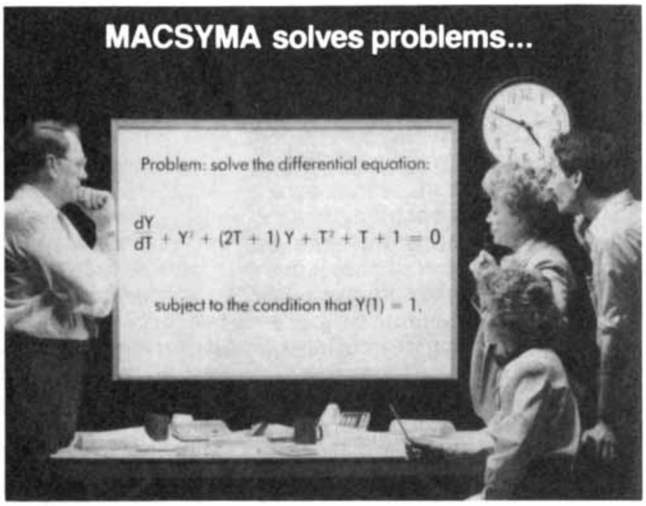

Problem: solve the differential equation:

$$\frac{dY}{dT} + Y^2 + (2T + 1)Y + T^2 + T + 1 = 0$$

subject to the condition that Y(1) = 1.

Symbolically...

```
(C1) DEPENDS(Y,T);
(D1)                         [Y(T)]
(C2) DIFF(Y,T) + Y ^  2 + (2•T + 1)•Y + T ^  2 + T + 1;
              dY     2                   2
(D2)          -- + Y  + (2T + 1) Y + T  + T + 1
              dT
(C3) SOLN:ODE(%,Y,T);                  T
                         %C  T %E  - T - 1
(D3)               Y = - -----------------
                                   T
                              %C %E  - 1
(C4) SUBST([T = 1,Y = 1], %);
                           %E %C - 2
(D4)                 1 = - ---------
                           %E %C - 1
(C5) SOLVE(%,%C),NUMER;
(D5)                        [%C = 0.5518192]
(C6) SPECIFIC_SOLN:SUBST(%, SOLN);
                                          T
                      0.5518192 T %E  - T - 1
(D6)             Y = - -----------------------
                                          T
                             0.5518192 %E  - 1
```

Numerically (In FORTRAN code.)

```
(C7)    FORTRAN(%)$
           Y = -(0.5518192•T•EXP(T) - T - 1)
        1         /(0.5518192•EXP(T) - 1)
```

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for two more years, he moved to the University of Washington. He joined Johnson & Johnson in 1979.

GERALD L. LIEDL ("The Science of Materials") is professor of materials engineering at Purdue University and head of the School of Materials Engineering. He began a 30-year association with Purdue as an undergraduate and continued it through graduate studies before joining the faculty there in 1959. He became full professor in 1978. Liedl's primary research areas are phase transformations in solids, X-ray diffraction and electron microscopy.

PRAVEEN CHAUDHARI ("Electronic and Magnetic Materials") is vice-president for science at the International Business Machines Corporation. Born in India, he got his undergraduate education at the Indian Institute of Technology in Kharagpur and then came to the U.S. to pursue graduate studies at the Massachusetts Institute of Technology, where he received his Sc.D. in 1966. He joined IBM the same year, working at the Thomas J. Watson Research Center. He took his current position in 1982.

J. M. ROWELL ("Photonic Materials") is assistant vice-president at Bell Communications Research (Bellcore) in the solid-state science and technology research laboratory. He was born and educated in England, where he studied at the University of Oxford. After getting his doctorate in 1961, he came to the U.S. and joined the technical staff of the Bell Telephone Laboratories, remaining there until the breakup of the Bell system in 1984. Since the breakup, Rowell writes, "obtaining a laboratory building has been a major preoccupation."

BERNARD H. KEAR ("Advanced Metals") is scientific adviser at Exxon's Corporate Research Center. All his academic degrees (a B.Sc., a Ph.D. and a D.Sc.) were earned at the University of Birmingham in England. He began his career as a research metallurgist in Britain but came to the U.S. in 1959 as a fellow of the Franklin Institute in Philadelphia. He then joined the Pratt & Whitney division of the United Technologies Corporation, where he investigated the structure, properties and processing of superalloys. He remained at United Technologies for 18 years before assuming his present position in 1981.

H. KENT BOWEN ("Advanced Ceramics") is professor of both ceramic engineering and electrical engineering at the Massachusetts Institute of Technology. He got his bachelor's degree in 1967 at the University of Utah and his doctorate at M.I.T. in 1971. He joined the M.I.T. faculty in 1970 in the department of materials science and engineering, and he later received a joint appointment in the electrical engineering and computer-science department. In 1976 he was made full professor. He also serves as director of M.I.T.'s manufacturing systems engineering and management program.

ERIC BAER ("Advanced Polymers") is Leonard Case Professor of Macromolecular Science at the Case Institute of Technology of Case Western Reserve University. He was born in Germany, was brought up in England and went to college in the U.S. After getting his Ph.D. in chemical engineering from Johns Hopkins University he went to work for E. I. du Pont de Nemours & Company, Inc. He joined the faculty at the University of Illinois in 1960, and went to the Case Institute in 1962. There he set up a comprehensive polymer science and engineering program, the first of its kind in the U.S. He headed the program for more than 16 years and oversaw its transformation into a department of macromolecular science. In 1978 Baer was appointed dean of the Case Institute.

TSU-WEI CHOU, ROY L. McCULLOUGH and R. BYRON PIPES ("Composites") are professors at the University of Delaware and members of its National Engineering Research Center for Composite Materials. Chou received a B.S. from the National Taiwan University, an M.S. from Northwestern University and a Ph.D. from Stanford University. In 1969 he joined the faculty at Delaware, becoming professor of mechanical engineering in 1978. Chou has held several visiting appointments at the Argonne National Laboratory and at universities in Great Britain, Germany, Argentina and South Africa. McCullough studied at Baylor University and the University of New Mexico, where he received his Ph.D. in 1960. After working for various private companies he was appointed professor of chemical engineering at Delaware in 1971. He is also associate director of the Center for Composite Materials. Pipes was director of the center before his appointment as dean of the College of Engineering in 1985. He obtained his doctorate from the University of Texas in 1972 while working for the General Dynamics Corporation. He then joined the faculty of Drexel University, and in 1974 he moved to Delaware.

COMPUTER RECREATIONS

The compleat computer caricaturist and a whimsical tour of face space

by A. K. Dewdney

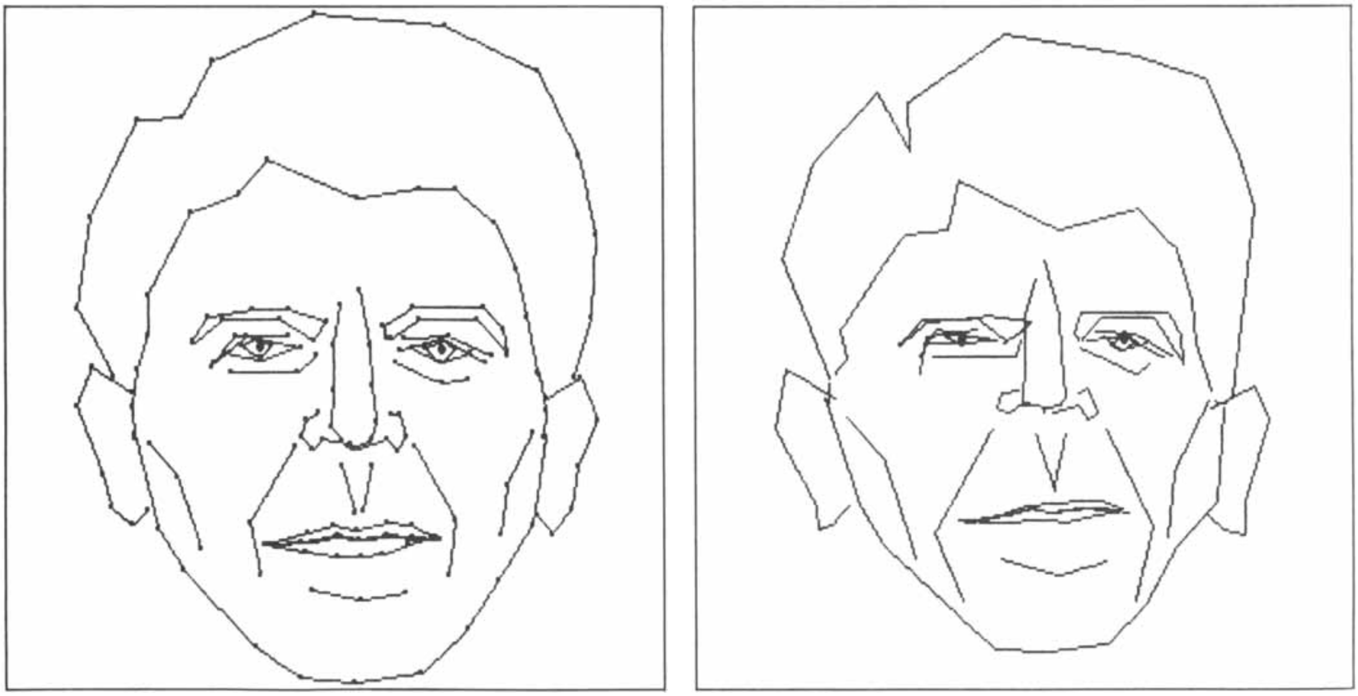
The face is unmistakable. There are the low, floppy ears, the prominent cheekbones, the high pompadour. Ronald Reagan's face is familiar around the world, but somehow it is even easier to spot his likeness in a caricature than it is in a photograph. Surely the art of caricature calls for deep insight into human nature. If this be the stuff of computation, surely the computer is a trivial adjunct—little more than a sketch pad—that merely stores the highly subtle renderings of the caricaturist in a visual form.

Or is it? The caricatures on these two pages and the following ones were all generated by a program devised by Susan E. Brennan, a staff scientist at the Hewlett-Packard Laboratories in Palo Alto, Calif. To run the program a mouse, a light pen or some other analogue of a pencil might be convenient, but they are certainly not essential. The results depend hardly at all on a steady hand or a practiced eye. Instead, once a photographic likeness of the face is entered into the computer, the program takes over and draws the caricature. How is it done? A short answer is deceptively simple: the program compares the photograph of the target face with an average face stored in the memory of the computer. The features that differ most from the average face are scaled up in size.

Brennan's program followed naturally from her own considerable abilities as a caricaturist and her interest in the cognitive processes underlying face recognition. Such processes have long baffled psychologists and cognitive scientists, and caricatures seem to play a special role in the process because when they are recognized, they are recognized almost instantly. Could it be that instead of remembering a friend's face, we remember a caricature of it? To address these issues Brennan invented her simple technique for generating caricatures, and she described it in her master's thesis at the Massachusetts Institute of Technology. She continues that interest in her spare time; in her working hours she now experiments with new forms of communication between human and computer that rely in part on natural language understanding.

Conceptually Brennan's technique is closely related to a trick that computer animators call in-betweening. Imagine two drawings of familiar objects, such as an apple and a banana, both done by connecting dots with lines [*see illustration on page 22*]. Each dot on the apple is then paired with a dot on the banana. If the paired dots are also connected by lines, the midpoints of the lines depict a brand-new fruit that splits the difference between the apple and the banana—a banapple, of course.

The same lines that connect the apple and the banana can also give rise to an extreme form of the banana—from the point of view, so to speak, of the apple. Extend each line beyond the banana by half its original length and then place dots at the end of the lines. When the dots are connected, the banana emerges in caricature. Similarly, by projecting the connecting lines be-



From realism to "facelessness" in FACEBENDER, *a program based on the work of* yond the apple, one can obtain a caricature of an apple—from the point of view of the banana. Faces can be treated in much the same way. Each pair of faces defines two mutual caricatures. The best caricatures, however, arise from comparison with a norm, or average face.

The norms in Brennan's program are made up from sets of several dozen real faces in a data base of several hundred. Points are chosen that outline the features of each face, and the points are labeled with respect to a set of matrix-based coordinate axes. The origin is at the upper left of the image plane, and the coordinates increase from left to right and downward. The scale is adjusted so that the left pupil is at the point (135,145) and the right pupil is at the point (190,145). The coordinates of corresponding points on each face are averaged to give the norm for that point. For example, the combined coordinates of the outer corner of the left eyebrow give the average coordinate for the outer corner of the left eyebrow of the average face. Three norms are constructed in this way: there is an average male face, an average female face and an average, overall plain-vanilla face. It is no surprise that the plain-vanilla face looks somewhat androgynous; it establishes the norm for most caricatures.

To draw a caricature based on the norm, the program must be supplied with a digitized version of a real face. In practice the face begins as a photograph, and the program prompts the user in turn for each of the 186 key points on the photograph. For instance, when the program calls for the six points that make up the left eyebrow, the user can respond by moving a mouse to successive points on the left eyebrow of the photographic image on the screen.

It is useful to think of Brennan's program as a fast shuttle for exploring what she calls face space. The entered coordinates for the points defining a photograph can be strung together in a predetermined order. The result is a list of numbers that can be treated as coordinates of a single point in a high-dimensional space. For example, both the average faces and the photographic face are represented by 186 points, each of which has two coordinates. The resulting list of 372 numbers for each face is a point in a 372-dimensional space. In principle every face can be assigned to a point in face space, and any two faces in face space can be connected by a straight line.

There is no need to be mystified over the concept of a higher-dimensional space. Face space is merely a handy abstraction for describing differences and similarities among faces. The familiar concepts of the straight line and the distance between two points have straightforward analogues in any higher-dimensional space. All the points along a straight line in face space represent proportional changes of each coordinate value. The distance between two points in face space is a measure of their similarity: similar faces are close neighbors in face space, and dissimilar faces are literally farther apart.

In face space one can imagine the norm as being near the center of a cloud of points representing realistic images of real faces. A line joins each real face to the norm. The points along the line correspond to a succession of intermediate faces that look increasingly like the real face. Beyond that face are the caricatures, but there is a natural limit to recognizable exaggeration: the caricatures eventually lose their human qualities and degenerate into a chaotic state Brennan calls facelessness.

The idea that every face is a point in face space suggests another fascinating transformation. Since any two faces in face space can be joined by a straight line, one can ask the program to generate a transitional sequence from one face to another. Brennan finds such sequences particularly intriguing when the two endpoint faces are male and female: the program effortlessly transforms Elizabeth Taylor into, say, the late John F. Kennedy.

The reader can duplicate some of Brennan's feats of caricature by writing a smaller version of her program; I call it FACEBENDER. It requires the user to supply at least two faces: a norm and the target face to be caricatured. I have referred above to the norm, whose coordinates have been generously provided by Brennan [*see upper illustration on page 27*]. The user must then convert the target face into the

Susan E. Brennan, with stops for caricatures of Ronald Reagan in between

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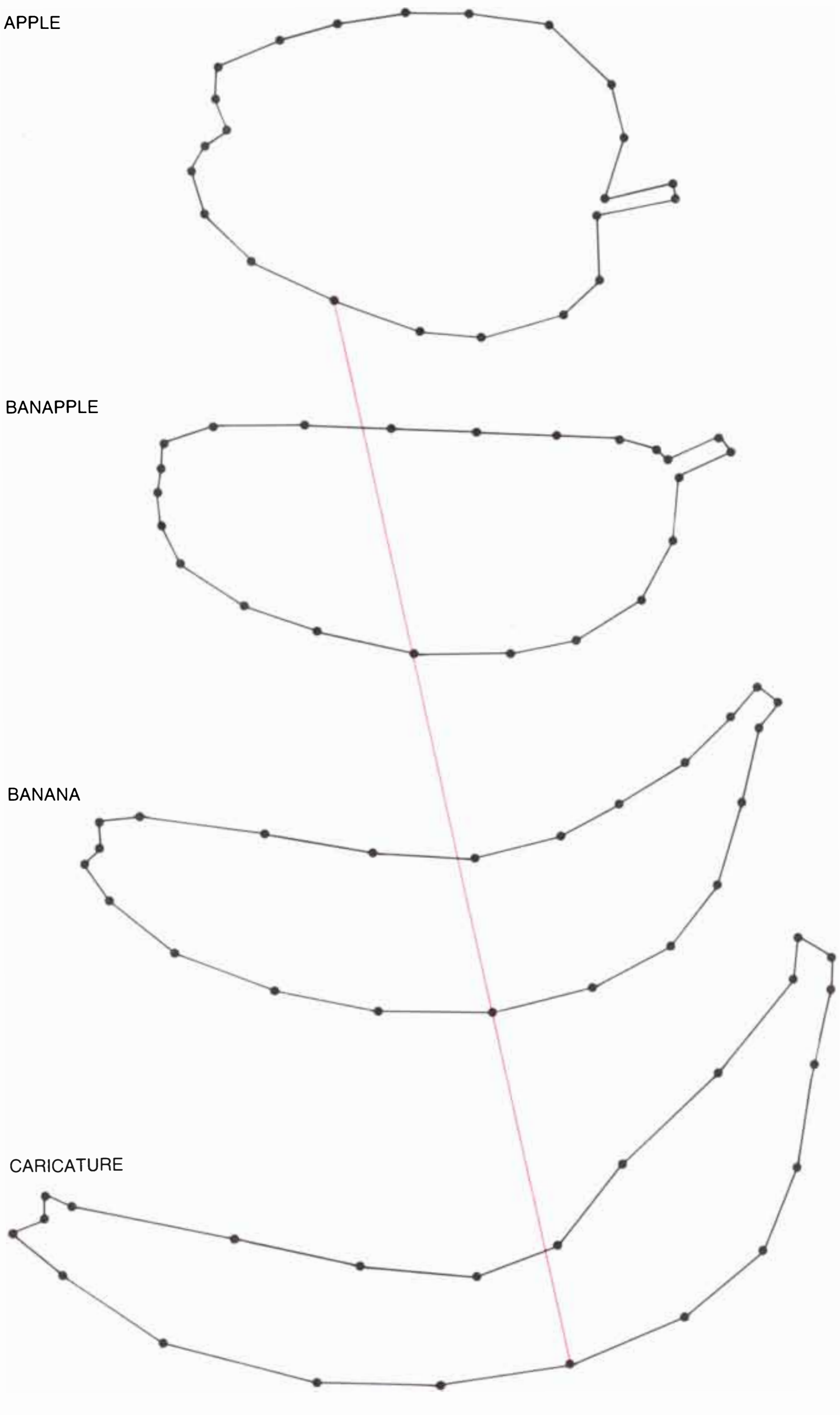
same form. In the absence of sophisticated digitizing equipment the reader can, with relatively little pain, convert a photograph of a loved one (possibly oneself) into a list of coordinates. Brennan warns, however, that the face in the photograph must have a bland, neutral expression; even a slight smile will grow to a monstrous grimace. The face must also be fully frontal; if the head is turned, FACEBENDER will turn it even more.

To determine the scale for the axes, assume the coordinates of the left and right pupils are the same as the norms: the left should be at (135,145) and the right at (190,145). (Remember that horizontal coordinates increase from left to right and vertical coordinates increase downward.) Once the distance scale is established the user must find the rest of the coordinates by careful measurement. In Brennan's digitizing scheme the points on the



How to turn an apple into a banana, and beyond

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Scientists are now working on new ways of treating such devastating afflictions as heart disease, cancer and Alzheimer's disease. They are testing new enzyme inhibitors that may control or reverse the late complications of diabetes. Forthcoming breakthroughs in understanding biological processes and treating disease may change the quality and perhaps the length of your life.

Medical research leading to such results takes years of patient, often frustrating experimentation by many different teams throughout the public and private sectors of our scientific community. The tasks involved are not simple.

Advances in research stem from a partnership that includes federal agencies such as the National Institutes of Health (NIH) and the Alcohol, Drug Abuse and Mental Health Administration (ADAMHA), universities and teaching hospitals across America, and private industry laboratories. Each partner often works independently to acquire knowledge and test new concepts. They must build on the knowledge developed in all laboratories, and they often coordinate efforts in their search for answers.

Whether an idea originates in a university laboratory or starts with basic product research carried on in the private sector, important findings percolate through the entire scientific community, where each new finding serves as a building block to establish a deeper understanding of what we are and how we function.

Medical research is an expensive process. It needs steady funding for equipment and personnel—even when progress is slow. Government and industry often work with university-based scientists and the medical profession not only in the acquisition of new knowledge and the development of new treatments, but also in funding these advances.

Now more than ever, we all must do our part to help keep the flow of discoveries active and ongoing. If funding for medical research is reduced, major advances in knowledge about some of the most dreaded diseases facing us today could be delayed for years to come.

What can you do?

- *Speak up*. Let your legislators know that you want funding of biomedical research by NIH and other government agencies to be kept at the highest possible levels.
- *Contribute* to voluntary health organizations supporting disease research.

Research-based pharmaceutical companies such as Pfizer are also increasing their financial investment in research. For instance, in 1984 alone, pharmaceutical companies in the United States spent over 4 *billion* dollars on research and product development.

At the same time, we at Pfizer realize the importance of committing more than money to research. As a partner in healthcare, we are continually working to discover new ideas, test new concepts, and turn new understanding to practical and beneficial uses. Now we are working harder than ever to make sure that this nation's medical research effort receives the attention—and funding—it deserves.

For more information on the future of medical research in America, write to Health Research U.S.A., P.O. Box 3852 FR, Grand Central Station, New York, NY 10163.

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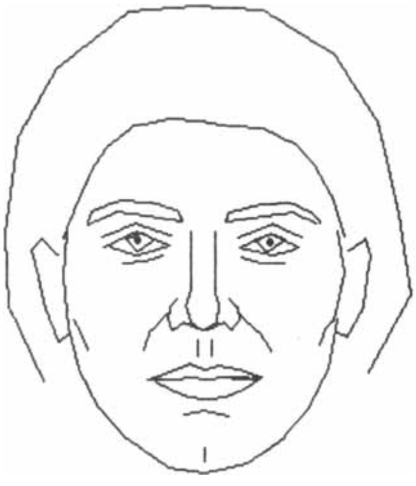


The androgynous average face

face are organized into 39 facial features; each feature is a succession of connected points. The order of the points depends on the orientation of the feature: for features that are mainly horizontal the points are listed from left to right, and for features that are mainly vertical they are listed from top to bottom.

Brennan admits that identifying the key points on a face is governed mostly by trial and error, but the president's face can be used as a guide. For this reason it is important that the same person carry out the conversion from photograph to list for each face entered into a data base.

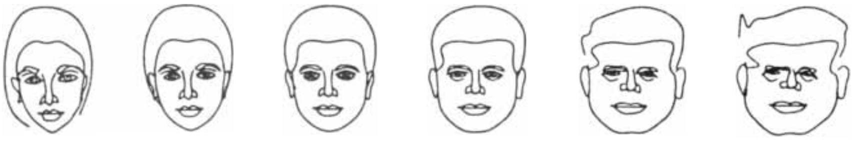
FACEBENDER stores the two digitized faces in arrays called *face* and *norm*. A third array called *disp* is needed to create a display. All three arrays have 186 rows and two columns: one face point per row and one coordinate per column. Points are arranged in the serial order given in the list for *norm*. The advantage of this ordering is that all lines in the final picture can then be drawn between successive points in the array; of course, lines are not drawn between successive array points when one feature is complete and another is about to be drawn.

The first feature the program draws is the pupil of the left eye; the second feature is the right pupil. Each pupil can be rendered as either a dot or a small circle; somehow the circles look friendlier. For the remaining features, however, lines are drawn to join consecutive points in the array. A special array called *features* is needed to skip the line between the last point in one facial feature and the first point in the next. The array gives the number of points in each feature, and a double loop supervises the skips [*see lower illustration on page 27*].

Because the first two features have already been drawn, the display routine begins with the third feature, namely the left iris. The first point in the left iris is the third point of the array *disp,* which is indexed by the variable i; hence the value of i is initially set equal to 3. The array *features* is indexed by another variable, j, and it ranges from 1 to 37 because there are 37 features left to draw. Within the j loop another variable called *count* keeps track of the number of lines drawn for each feature; it increases by 1 with each passage through the j loop. The index i is also increased with each passage through the loop; it identifies the point in the array *disp* that is currently participating in the frantic exercise of connect-the-dots.

Inside the j loop is a second loop called a while loop; it compares the number of points joined so far in feature j with the total number of points in that feature. The program leaves the while loop when the two numbers are equal; the feature is complete. If there are still points to connect in the feature, the program draws a line from point i in the array *disp* to point $i + 1$. My notation is merely shorthand. A real display command would call for a line from the point whose coordinates are $disp(i,1)$ and $disp(i,2)$ to the point whose coordinates are $disp(i + 1,1)$ and $disp(i + 1,2)$.

The heart of FACEBENDER is its exaggeration routine. Its structure is even simpler than the display routine I have just outlined [*see lower illustration on page 27*]. For each of the 186 facial points in the arrays *face* and *norm,* the loop calculates a new array called *bend.* The new array encodes the caricature-to-be. Each coordinate of the array *bend* is calculated by adding the corresponding coordinate of the array *face* to a quantity that exaggerates the differences between *norm* and *face.* The exaggeration factor f is typed in by the user; f then multiplies the difference between the horizontal coordinates of *face* and *norm,* and it also multiplies the difference between the vertical coordinates.



Elizabeth Taylor (as Cleopatra) meets former President Kennedy in face space

The only things left to do are to organize the program and, optionally, to tune up the drawing routine. A simple, nonprocedural approach to organization is to place both the display routine and the exaggeration routine inside an interactive loop that asks the user: "Want to try another?" The program must also prompt the user for the exaggeration factor. Arrange the prompt so that a number of different exaggeration factors can be tried without having to reenter the array *face;* their effect on the caricature is then easy to compare.

The drawings can be somewhat enhanced if the dots are connected with so-called spline curves instead of with straight lines. Splines avoid zigs and zags and connect the dots smoothly; Brennan's program usually draws spline curves to form the smooth contours of facial features. Nevertheless, I was aware that splines might prove sticky to explain in a column that is devoted largely to easy programs. I asked Brennan for an alternate method. Could straight lines be used instead? Much to her surprise and mine, caricatures drawn with straight lines are almost as good as the ones drawn with splines. Indeed, all her images appearing here were drawn using straight lines. With only a small loss in aesthetic value the programmer can avoid a most troublesome technique. One can immediately set about digitizing a favorite photograph.

Brennan's caricature generator has been applied in several studies of facial recognition. Faces from her program have been transmitted over telephone lines as part of an experiment in teleconferencing at the Massachusetts Institute of Technology Media Laboratory. Last year she did an experiment with Gillian Rhodes of the University of Otago in New Zealand, who was then a graduate student working with Roger N. Shepard of Stanford University. First she generated caricatures of faculty members and students in the psychology department at Stanford. The caricatures were then tested for recognizability against standard line drawings.

Brennan has summarized the findings: "The caricature generator was particularly useful for this study because it enabled us to generate stimuli that varied in a continuous and controlled way; previous perceptual studies have had to compare caricatures with photos or other kinds of not-so-similar images, and have therefore not been free of representational effects. Caricatures were not found to be particularly *better* as recognizable representations (the 'best' representations were only modestly exaggerated), but

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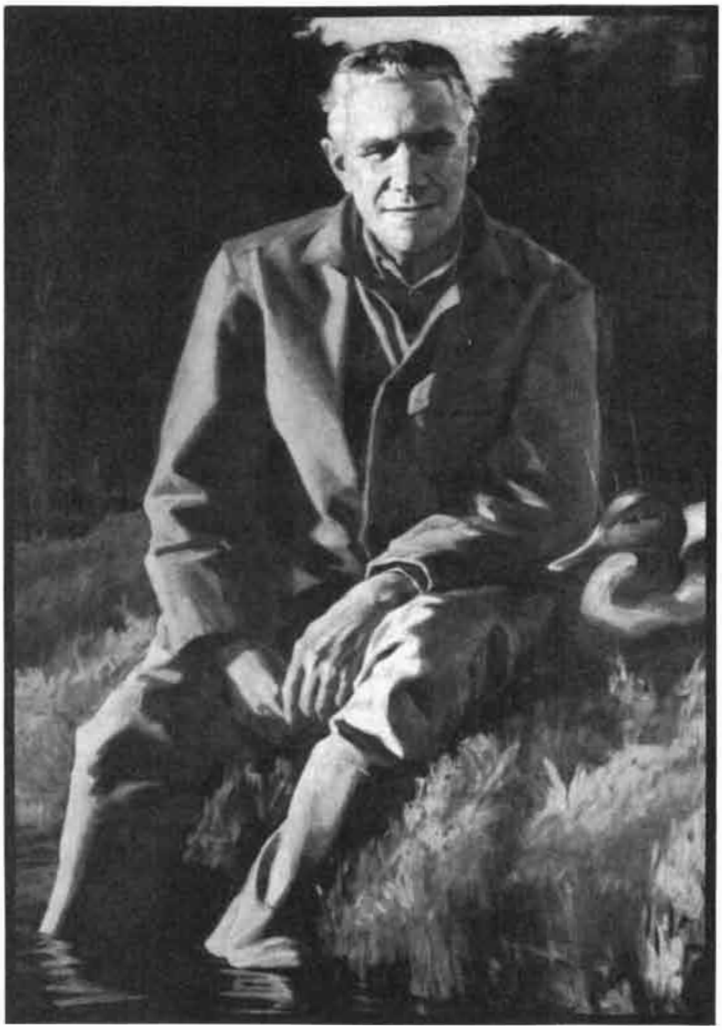

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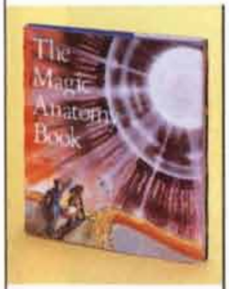

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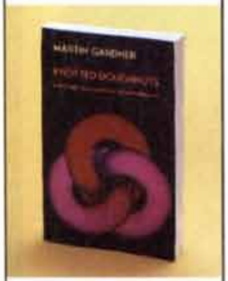

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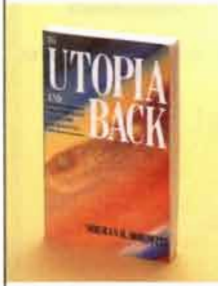

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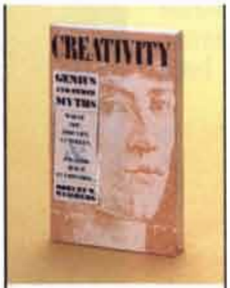

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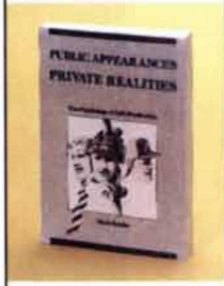

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when the highly exaggerated caricatures were recognized, they were recognized significantly *faster*—about twice as fast, in fact, as the realistic line drawings of the same people."

Brennan suggests a number of other experiments with the caricature generator. For example, it would be fascinating to recover the "norm" assumed by human caricaturists. Handed a caricature of a given subject by a given artist, she would try reversing the exaggeration to determine the normal face, presumably lodged somewhere in the artist's unconscious mind, from which the exaggeration was derived. Would

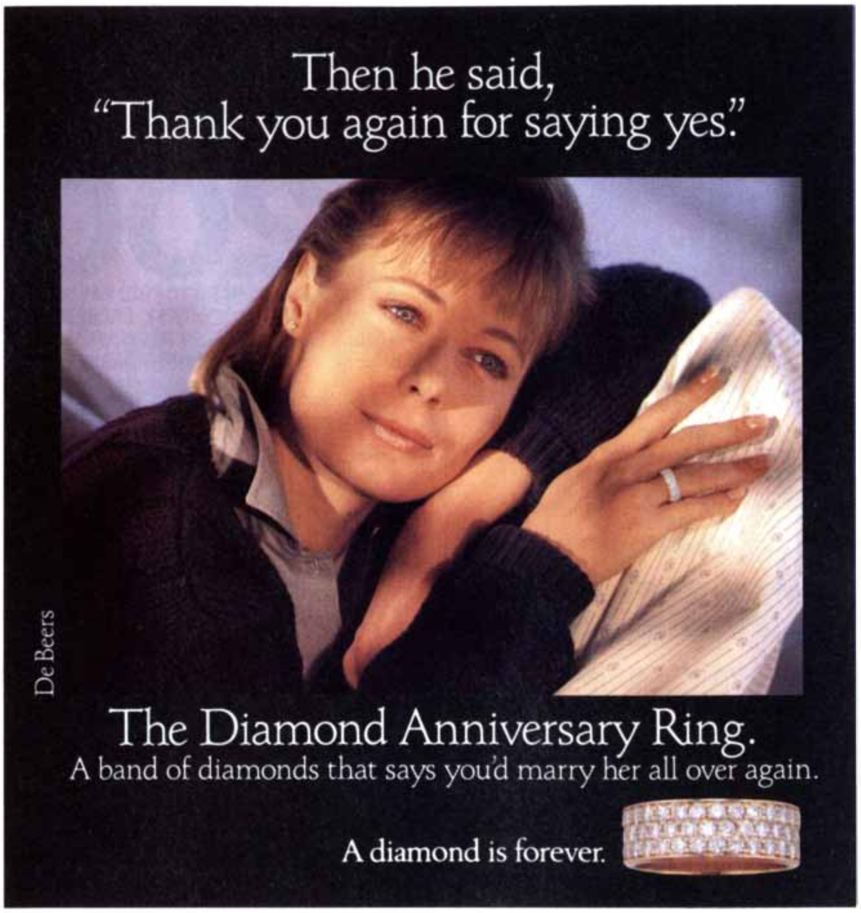
LEFT PUPIL	1 POINT	(135,145)
RIGHT PUPIL	1 POINT	(190,145)
LEFT IRIS	5 POINTS	(134,141) (128,144) (133,149) (140,144) (135,141)
RIGHT IRIS	5 POINTS	(190,141) (184,144) (189,149) (196,144) (190,141)
BOTTOM OF LEFT EYELID	3 POINTS	(119,147) (133,140) (147,146)
BOTTOM OF RIGHT EYELID	3 POINTS	(177,147) (190,141) (203,147)
BOTTOM OF LEFT EYE	3 POINTS	(121,147) (133,150) (147,146)
BOTTOM OF RIGHT EYE	3 POINTS	(177,147) (191,150) (201,148)
TOP OF LEFT EYE	3 POINTS	(118,143) (132,137) (148,142)
TOP OF RIGHT EYE	3 POINTS	(176,143) (191,137) (204,143)
LEFT EYE LINE	3 POINTS	(127,154) (135,153) (144,150)
RIGHT EYE LINE	3 POINTS	(178,151) (187,154) (196,154)
LEFT SIDE OF NOSE	6 POINTS	(156,140) (156,153) (156,165) (154,172) (156,179) (161,182)
RIGHT SIDE OF NOSE	6 POINTS	(166,140) (166,153) (166,166) (168,172) (167,179) (161,182)
LEFT NOSTRIL	6 POINTS	(150,169) (147,173) (146,178) (148,182) (153,179) (161,182)
RIGHT NOSTRIL	6 POINTS	(173,169) (176,172) (177,178) (174,182) (170,179) (163,182)
TOP OF LEFT EYEBROW	6 POINTS	(112,137) (113,132) (125,127) (139,128) (150,131) (152,136)
TOP OF RIGHT EYEBROW	6 POINTS	(171,136) (173,132) (186,129) (199,128) (208,132) (211,137)
BOTTOM OF LEFT EYEBROW	4 POINTS	(112,138) (124,132) (138,134) (152,136)
BOTTOM OF RIGHT EYEBROW	4 POINTS	(171,136) (187,134) (200,132) (210,137)
TOP OF UPPER LIP	7 POINTS	(137,203) (149,199) (156,196) (162,199) (168,197) (177,199) (187,202)
BOTTOM OF UPPER LIP	7 POINTS	(138,203) (148,203) (156,202) (163,203) (170,202) (178,203) (186,202)
TOP OF LOWER LIP	7 POINTS	(138,203) (149,203) (156,202) (163,203) (170,202) (177,202) (186,203)
BOTTOM OF LOWER LIP	7 POINTS	(141,204) (148,207) (155,210) (163,211) (171,210) (179,207) (185,203)
LEFT SIDE OF FACE	3 POINTS	(103,141) (101,160) (104,181)
RIGHT SIDE OF FACE	3 POINTS	(219,140) (222,159) (218,179)
LEFT EAR	7 POINTS	(99,150) (92,144) (88,149) (90,160) (94,174) (99,187) (104,184)
RIGHT EAR	7 POINTS	(224,149) (231,144) (234,151) (232,160) (230,173) (224,185) (219,184)
JAW	11 POINTS	(104,181) (108,199) (115,214) (129,228) (147,240) (162,243) (180,239) (196,228) (207,215) (215,199) (219,178)
HAIRLINE	13 POINTS	(101,144) (107,129) (114,114) (120,104) (131,95) (146,92) (160,93) (174,95) (188,96) (201,103) (210,114) (217,126) (222,143)
TOP OF HEAD	13 POINTS	(93,204) (78,173) (76,142) (82,101) (99,70) (129,46) (158,44) (188,45) (217,64) (236,94) (245,134) (250,168) (233,200)
LEFT CHEEK LINE	3 POINTS	(145,175) (139,182) (135,190)
RIGHT CHEEK LINE	3 POINTS	(178,176) (185,183) (190,191)
LEFT CHEEKBONE	3 POINTS	(105,178) (109,184) (112,190)
RIGHT CHEEKBONE	3 POINTS	(218,178) (214,183) (211,189)
LEFT UPPER LIP LINE	2 POINTS	(159,186) (159,193)
RIGHT UPPER LIP LINE	2 POINTS	(165,186) (165,193)
CHIN CLEFT	2 POINTS	(162,232) (162,238)
CHIN LINE	3 POINTS	(153,218) (162,216) (173,219)

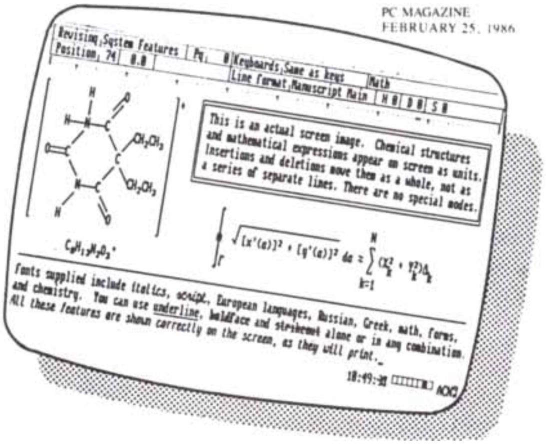
The coordinates for the points of an average face

```
DISPLAY ROUTINE
i ← 2
for j = 1 to 37
  i ← i + 1
  count ← 1
  while count < features(j)
    draw line from disp(i) to disp(i + 1)
    count ← count + 1
    i ← i + 1
```

```
EXAGGERATION ROUTINE
for i = 1 to 186
  bend(i,1) ← face(i,1) + f × [face(i,1) – norm(i,1)]
  bend(i,2) ← face(i,2) + f × [face(i,2) – norm(i,2)]
```

The heart of FACEBENDER





This is an actual screen image. Chemical structures and mathematical expressions appear on screen as units. Insertions and deletions move them as a whole, not as a series of separate lines. There are no special modes.

Fonts supplied include italics, script, European languages, Russian, Greek, math, forms, and chemistry. You can use underline, boldface and strikeout alone or in any combination. All these features are shown correctly on the screen, as they will print.

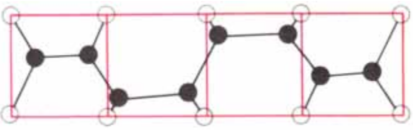
the reconstructed norm be much the same from one subject to the next? Would different artists assume different norms?

Flight simulators that run on home computers were featured in this department for July. For owners of the Microsoft product H. R. Newhall of Springfield, Mass., suggests that daring pilots attempt a loop over the Manhattan Bridge. At the bottom of the loop fly under the bridge.

Faster games are available. John J. Kasianowicz of Port Jefferson, N.Y., likes JET, marketed by the SubLogic Corporation of Champaign, Ill., and written by Charles Guy and Bruce A. Artwick. The action is much faster in JET than it is in other such programs, and one can engage in free flight, low bombing runs and aerial dogfights. Kasianowicz, who admits to being something of a devil, strafes his home airport and continually probes the limits of the program. There is an amusing problem with the scenery: it is possible to fly through mountains without crashing. Kasianowicz guns his aircraft straight into the side of a mountain, pulls back on the stick and zooms out through the top.

Readers too numerous to mention found ways to improve the minimal lengths of the 10-by-10 and the 22-by-22 Steiner trees given in Martin Gardner's guest column in June. In both cases a slightly different seven-point subtree reduced the length by about .005. Nevertheless, the new trees also proved to be nonminimal. Eric Carlson of Cambridge, Mass., included a 10-point subtree in the 22-by-22 square to reduce the length of the square to 440.009.... Ronald L. Graham of AT&T Bell Laboratories then found a way to include the same subtree in the 10-by-10 square, reducing it to a length of 90.30664....

Many readers noted that the solution for the 4-by-9 rectangle, given in July, was incorrectly drawn, although the stated minimal length was correct. The problem arose in the drawing of the 2-by-5 subtree along the middle of one of the long sides; the correct version of the subtree is shown below. Other readers suggested ways in which minimal Steiner trees could be generalized to lattices of points in three dimensions as well as to two-dimensional surfaces other than the plane.



Shortest 2-by-5 Steiner tree known

They look like sunglasses.

Vision Breakthrough

When I put on the pair of glasses what I saw I could not believe. Nor will you.

By Joseph Sugarman

I am about to tell you a true story. If you believe me, you will be well rewarded. If you don't believe me, I will make it worth your while to change your mind. Let me explain.

Len is a friend of mine who has an eye for good products. One day he called excited about a pair of sunglasses he owned. "It's so incredible," he said, "when you first look through a pair, you won't believe it."

"What will I see?" I asked. "What could be so incredible?"

Len continued, "When you put on these glasses, your vision improves. Objects appear sharper, more defined. Everything takes on an enhanced 3-D effect. And it's not my imagination. I just want you to see for yourself."

When I received the sunglasses and put them on I couldn't believe my eyes. I kept taking them off and putting them on to see if indeed what I was seeing through the glasses was indeed actually sharper or if my imagination was playing tricks on me. But my vision improved. It was obvious. I kept putting on my cherished $100 pair of high-tech sunglasses and comparing them. They didn't compare. I was very impressed. Everything appeared sharper, more defined and indeed had a greater three dimensional look to it. But what did this product do that made my vision so much better? I found out.

DEPRESSING COLOR

The sunglasses (called BluBlockers) filter out the ultraviolet and blue spectrum light waves from the sun. You've often heard the color blue used for expressions of bad moods such as "blue Monday" or "I have the blues." Apparently, the color blue, for centuries, has been considered a rather depressing color.

For eyesight, blue is not a good color too. There are several reasons. First, the blue rays have the shortest wavelength in the visible spectrum (red is the longest). As a result, the color blue will focus slightly in front of the retina which is the "focussing screen" onto which light waves fall in your eye. By eliminating the blue from the sunglasses through a special filtration process, and only letting those rays through that indeed focus clearly on the retina, objects appear to be sharper and clearer.

The second reason is even more impressive. It is not good to have ultraviolet rays fall on our eyes. Recognized as bad for skin, uv light is worse for eyes and is believed to play a role in many of today's eye diseases. In addition, people with contact lenses are at greater risk because contacts tend to magnify the light at their edges thus increasing the sun's harmful effects.

Finally, by eliminating the blue and uv light during the day, your night vision improves. The purple pigment in your eye called Rhodopsin is affected by blue light and the eyes take hours to recover from the effects.

SUNGLASS DANGER

But what really surprised me was the danger in conventional sunglasses. Our pupils close in bright light to limit the light entering the eye and open wider at night—just like the aperture in an automatic camera. So when we put on sunglasses, although we reduce the amount of light that enters our eyes, our pupils open wider and we are actually allowing more of the blue and ultraviolet portions of the light spectrum into our eyes.

BluBlockers sunglasses are darker at the top to shield out overhead light. The lens used is the CR-39 which most eye doctors will tell you is one of the finest materials you can use for glasses and is manufactured under license.

The frames are some of the most comfortable I have ever worn. The moulded nose rest will fit any nose. The hinge causes the frames to rest comfortably on your face and can be adjusted for almost any size face.

We also have a clip-on pair that weighs less than one ounce. Both come with a padded carrying case and an anti-scratch coating.

I urge you to order a pair and experience the improved vision. Then take your old sunglasses and compare them to the BluBlockers. See how much clearer and sharper objects appear with BluBlockers. And see if your night vision doesn't improve as a direct result. If you don't see a dramatic difference in your vision—one so noticeable that you can tell immediately, then send them back anytime within 30 days and I will send you a prompt and courteous refund.

DRAMATIC DIFFERENCE

But from what I've personally witnessed, once you use a pair, there will be no way you'll want to return it.

Astronomers from many famous universities wear BluBlockers to improve their night vision. Pilots golfers, skiers, athletes—anyone who spends a great deal of time in the sun have found the BluBlockers indispensable.

Our eyes are very important to us. Protect them and at the same time improve your vision with the most incredible breakthrough in sun glasses since they were first introduced. Order a pair or two at no obligation, today.

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BOOKS

From waterpower to space telescopes, and on to quantum electrodynamics and clover

by Philip Morrison

A HISTORY OF INDUSTRIAL POWER IN THE UNITED STATES, 1780–1930: VOLUME 1, WATERPOWER IN THE CENTURY OF THE STEAM ENGINE; VOLUME 2, STEAM POWER, by Louis C. Hunter. The University Press of Virginia (Volume 1, out of print; Volume 2, $50). Read of what Odysseus found on his return, in the translation by Robert Fitzgerald: "His own handmills were there, / and twelve maids had the job of grinding out / whole grain and barley meal, the pith of men." While the crowd of Penelope's suitors sat eager to be fed "so dainty in Odysseus' hall," the everyday task of her women was grievous.

Seldom would any farmwife in the newly independent states receive so many demanding guests as beset the lonely Queen of Ithaca. Yet 30 centuries later every American farm family still took its daily bread from meal or flour. The preparation of the grain, by hand quern or pounding mortar, demanded several hours of hard work each day; the coarser meal made a staple food much less palatable than that from mill-ground flour.

The water-driven gristmill freed the farmsteads of our still rural economy from the daily grind. A prudent farmer would ride long and hard with a sack of grain to save his family's labor; a gristmill at a distance of 25 miles was "a valuable consideration when compared with mortar and pestle." Soon the water-powered sawmill joined the gristmill along ponded streams. "The ax produces the log hut, but not till the sawmill is introduced do framed dwellings and villages arise; it is civilization's pioneer machine," wrote an enthusiast as late as 1850. With sawed lumber available, board floors could replace dirt and tight walls protect the homesteaders from the drafty chinks between logs.

In 1840 a census counted up some 70,000 water mills in the U.S., producing grist or sawed lumber and each serving on the average about 300 people spread over an area of 10 or 20 square miles. In the typical mill one or two men operated a waterwheel delivering in season a couple of kilowatts to a single pair of millstones or a single reciprocating saw. Of course, work animals drawing plow and wagon were much more important power sources for the farmer than any mills, however welcome; in that same census four million horses were counted. Allowing for draft oxen as well, the power available from animals on farms was close to two orders of magnitude greater than that from water; perhaps the work done by the untiring mills was somewhat more significant than their contribution to the output of power.

So far all is prelude. Water mills are not yet industrial waterpower; communities of largely self-reliant smallholders who buy and sell little have not yet formed a market economy. To be sure, the millwright has appeared, a knowing and versatile mechanic, forerunner of the mechanical engineer. Yet even the occasional larger mills were mainly wood mechanisms, in which at most a couple of hundred pounds of iron served as bearings and fastenings.

Millwright, carpenter, blacksmith and mason together can fashion such mills and design and build the requisite millponds and races. Those craftsmen and their materials are old village fixtures, widespread and familiar.

Waterpower first appears on an industrial scale in textile manufacture, particularly cotton. The entrepreneurial energy and amassed capital of wealthy commercial Boston turned from investment in foreign commerce under sail power to the exploitation of New England rivers, first of all on the Charles and the Merrimack. The rule of thumb applied by the millwright working to harness some narrow country creek gave way to the civil-engineering expertise behind the extensive dams and canals begun in about 1820 around the falls of the lower Merrimack at Lowell (the Great Falls of the Passaic were developed even earlier). In the 1850's the 10 mills at Lowell housed 300,000 spindles tended by many thousands of workers, mostly women. Five miles of controlled hydraulic masonry-lined canals, which were carefully surveyed, profiled and gated, furnished some eight megawatts of secure power, as much as a few thousand country mills could generate. The American industrial city was unlike anything in Europe. It was more or less a company town; waterpower shaped it and drove it. (The current development in Lowell of a National Industrial Park offers a remarkable opportunity to revisit this phenomenon.)

The New England model, careful hydraulic design under monopolistic investment and control, strongly influenced both technology and management throughout the country. The apotheosis of the country mill arose at the grand cataract at the head of navigation on the Mississippi at Minneapolis. By 1880 the waterpower developed there exceeded the yield of the entire Merrimack severalfold; the timber and grain of the broad valley of the Mississippi fed the big mills run by those falls. By 1900 that site had become the largest flour- and lumber-mill center in the world, and much the largest industrial center based on waterpower, the general mills.

Louis C. Hunter's bulky, well-illustrated and well-written volumes are so rich and clear that Volume 2's account of steam power is illuminated by the narrative of waterpower. Stationary steam power first came to America as it had come in Britain, in the ponderous form of the atmospheric Newcomen engine, applied to draining water from mines. In 1787 the impressive specimen in Cranston, R.I., burned a couple of cords of wood each day. It had a piston almost three feet in diameter that 10 times a minute rocked up and down a beam "near four feet in diameter and 20 feet long" made of two massive oak timbers. The device developed slightly more power than one of contemporary millwright Oliver Evans' country-built waterwheels. Its advantage lay in the fact that iron mines do not always lie along convenient millstreams.

Seaports and navigable rivers supported early centers of trade. There the people came as cities grew. Harbors and broad rivers are hardly waterpower sources. Steam transport burgeoned, fueled by wood. By 1838 the steam power installed nationally was about half as much as the power of all those 70,000 country water mills, but it was delivered by only 3,000 engines. More than 60 percent of the total steam power then was mobile, driving 1,200 steamboats and locomotives. The 1,800 standing steam engines were generally in cities, except

Advertisement

Performing to Meet the Challenge of Change

As the marketplace challenges current technology by demanding materials with higher performance capabilities, Phillips Petroleum Company meets the challenge with a breakthrough in advanced thermoplastic materials.

Based on their pioneering work in the discovery of high density polyethylene and polypropylene, and their expertise in the manufacturing of Ryton® polyphenylene sulfide (PPS) engineering plastics, Phillips researchers began work over eight years ago to develop the composite materials and the manufacturing processes that the marketplace is looking for today.

The result is a new generation of advanced materials which represent the state of the art in composites. Industry sources claim Phillips "redefined" polymer composites when they introduced tough, high temperature thermoplastic materials with exceptional chemical resistance and low flammability. In fact, *Industrial Research* magazine recognized Phillips Advanced Composites as one of the top 100 developments of 1985.

A significant introduction.

The marketplace was quick to see the significance of these new materials. Two companies which began incorporating the materials into new products being manufactured were presented design awards by the Society of the Plastics Industry in 1986. But the utilization of these composites in actual applications tells the whole story.

Withstanding the rigors of oil production.

For instance, the oil industry needed a means to prevent the wear on downhole tubing by sucker rods used to pump crude oil to the surface. Some means of centering the sucker rod in the tubing—a sucker rod "guide"—was the answer. It was imperative that the sucker rod guide resist wear in extremely hot, corrosive environments. It had to withstand the abrasion of an oil well and remain locked in place no matter how severe the conditions. And for ease and economy, it had to have the capability of being installed in the field, so that oil production would not be hindered.

Phillips Advanced Composites were selected by J.M. Huber Co., an oil field equipment supplier, for use in these guides because they met and exceeded the performance and cost needs of the application. The guides were molded from a glass reinforced polyphenylene

(continued)

Sucker rod guides were developed from Phillips Advanced Composites to resist the corrosive, abrasive environments of an oil well, survive rough installations and withstand high temperatures.

A unique leg brace was developed by shaping rods to fit the exact contours of the patient's leg. And since the brace is lightweight, the patient's recovery time is shortened.

sulfide stampable sheet and were easily installed using conventional equipment. This material contains long fibers which can be formed into complex shapes yet resists the heavy hand of the oil field roughneck during installation and downhole temperatures as high as 400°F.

Discovery by the medical profession.

Toughness and chemical resistance are not always needed for every application. Garry Ogilvie, a certified orthotist at Hillcrest Medical Center in Tulsa, Oklahoma, heard about Phillips Advanced Composites at a model airplane flying contest. He saw a use for the materials in his work building braces because of the material's excellent strength to weight ratio.

Using rods of graphite fiber and polyphenylene sulfide developed and produced by Phillips Shape Form Composites Process, he was able to make a unique leg brace. The rod can be shaped to the exact contours of the patient's leg by simply heating and bending it around a plaster cast. The composite brace is faster to fabricate and fit, and it weighs less than a comparable metal one. Thus, the patient's recovery is shortened.

Increased safety in flight.

Another area where advanced thermoplastic materials are needed is the aircraft industry. New government regulations will require major airlines to switch to materials inside the cabin which do not burn easily. Yet the materials must be lightweight so that the plane remains fuel efficient. Phillips Advanced Composites, which incorporate polyphenylene sulfide polymers, are some of the most fire safe materials available. In 1977 NASA rated polyphenylene sulfide the most fire safe plastic of any tested. Recent fire testing on composite materials containing PPS have shown that these high strength materials will meet or exceed the new stringent government regulations. As a result of the change to these materials, the flying public will benefit from increased fire safety and airlines will retain the benefit of lightweight construction techniques required for fuel efficient operations.

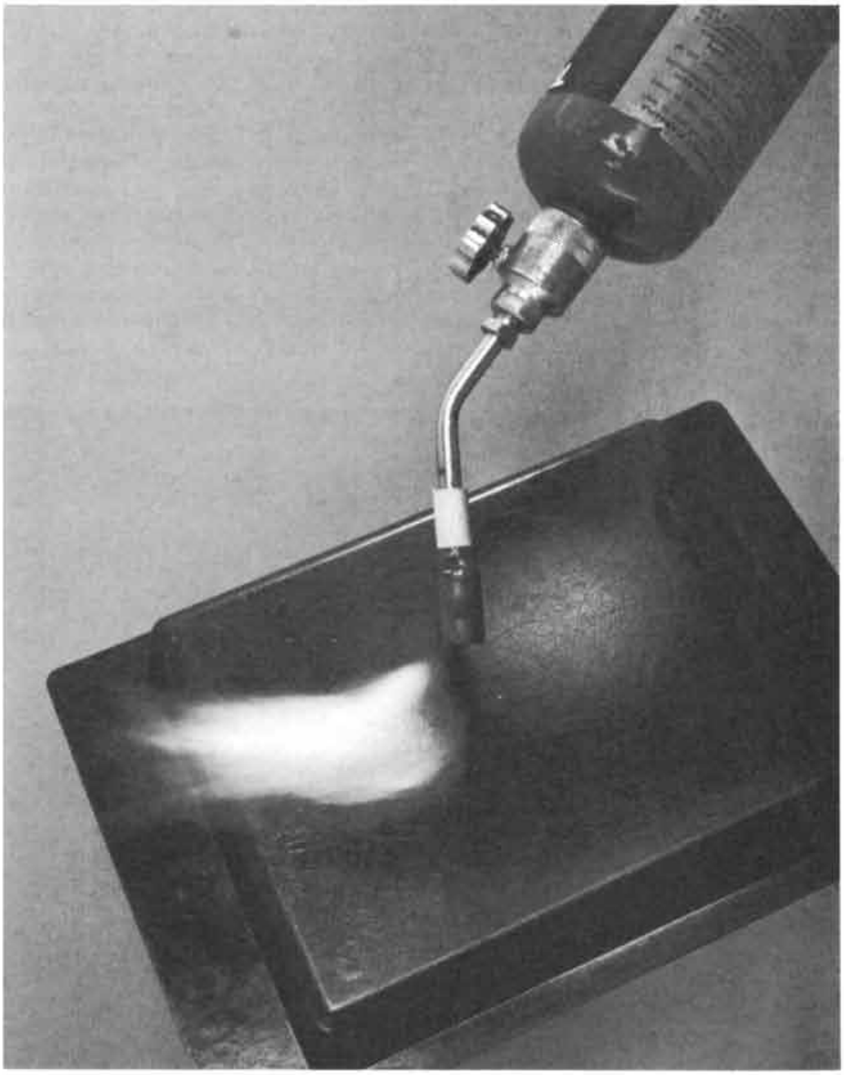
What about the future?

Phillips Advanced Composites are presently being evaluated for use on new "high performance" military aircraft which will cruise three times faster than the speed of sound. High temperature-resistant materials are required because aerodynamic heating during flight at these speeds produces temperatures above 300°F on the wings and other exterior components of the plane.

But temperature is only half the concern. The plane must still be lightweight so that a pilot can maneuver easily to evade an enemy. Only Advanced Composites can give that kind of performance.

And performance will continue to be the challenge in the changing marketplace for new materials. Phillips Advanced Composites are meeting that challenge head on.

For more information, contact Advanced Composites, Phillips Petroleum Company, Phillips Research Center, Bartlesville, Oklahoma 74004. Phone: (918) 661-1984.



A new lightweight fire safe material developed with Phillips Advanced Composites, meets or exceeds the new government regulations on aircraft interiors, as well as retains fuel efficiency.

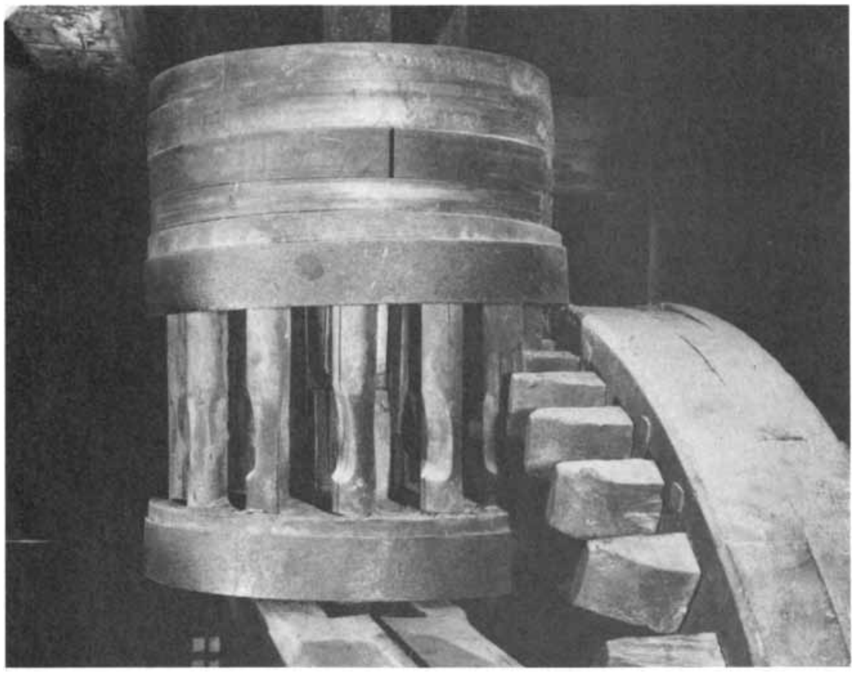
in the southern states, where the scarcity of millstreams and the need for processing such plantation staples as rice and sugar impelled countryside milling by steam. One remarkable table from the 1838 census shows that half of the stationary steam power still went to the old uses, processing grain, sugar and wood, or pumping and pounding. The other half drove newer forms of industry, spinning cotton, rolling iron, blowing foundry furnaces, making cut nails, even printing on textiles and paper.

City use of the steam engine was joined to city production of the steam engine. As steam offered power for urban manufacture, the urban machinist and metalworker, able to shape iron first by hand and later by machine tool to tolerances unknown in the millwright's bulky wood gearing, became the typical artisan of the new power source. The old trades of carpenter and mason were less in demand.

Soon the high-pressure noncondensing engine came to be standard. "The ponderous beam engine see-sawing slowly in a massive engine house" was replaced by a much faster, smaller, simpler and cheaper engine. It was less efficient, its power output was lower, yet its power density was much higher.

"Watt," wrote one author, "had nothing whatever to do with the invention of the American steam-engine...an engine producing power by heat, and not by heat and cold." The mill engine was much less thirsty than that of Matthew Boulton and James Watt; a 10-horsepower noncondensing engine could be watered with a bucket, whereas a similar condensing engine demanded power pumps to supply 30 times as much feedwater. It was Richard Trevithick of Cornwall and Oliver Evans of eastern Pennsylvania who developed the noncondensing engine, running at a few atmospheres of steam pressure. (The versatile Evans was both the mentor of American country millwrights and a pioneer in the design and manufacture of iron steam engines.) Watt used input steam at a fifth of an atmosphere, but he cooled the exhaust steam to water in a condenser, pulling most of his overall one atmosphere of pressure difference "out of the blue sky."

There is a fine account of boiler design and manufacture, a topic neglected by the early engineers, since a boiler is a static item giving little pleasure next to the showy and ingenious valve gear and the noble piston slides. The boiler is the soul of the engine, and its thermal and structural virtues are invisible. Many boilers duly blew up, often fatally on crowded steamboats. Rational thermal and pressure design came slowly, alongside of insurance and inspection. Hydraulic and steam-worked power machinery for constructing boilers arrived in the 1880's. Such devices formed and joined thick plates better than any blacksmith shop could even with its steam trip hammer. It is noteworthy that boiler explosions became a subject of profound public-policy concern in late Victorian times even though they were less of a risk to the public by an order of magnitude than are the well-tolerated automobile accidents of our time.



Wood gearing in a 19th-century gristmill

Steam power raised by coal first exceeded that raised by fuelwood sometime in the 1850's. The emergence of the new Corliss engine during the same decade offers another technical chapter of interest. George Corliss introduced a complex valve gear that used the flyball governor to control not the main throttle valve but instead stroke by stroke the cutoff time for steam entry into the cylinder. The outcome was a more economical engine well adapted to changes in load. Manufacture and promotion were expertly done; the big engines became a worldwide eye-catching success among users of high power; Corliss became the most celebrated American engineer of his time.

The full rationalization of steam-engine design by thermodynamics began in the 1860's. It is treated here rather briefly. We remain today in the Age of Steam and Water as far as stationary power is concerned; the great bulk of us read by power generated by spinning turbines, the fruit of high Edwardian technology, along with the water-tube boiler suited to really high steam pressures. Steam turbines are excluded from Hunter's account, although the earlier hydraulic turbines are treated.

Each volume ends memorably in anticlimax, the fate of 19th-century technology both for wheels spun by water and for stationary reciprocating steam. It was the electrical distribution of subdivided power, a technology that became important in about 1900, that transformed industry and made obsolete these other power sources. Today's factories hardly know of expanding steam or falling water, even though their power still derives from just those motions. The concept of the subdivision of power was first realized in American mills. The main shafts of waterwheel or piston engine generated power that traveled through a fantastic array of whirling leather belts linking wheeled shafts floor to floor, driving each loom or lathe. Although they were awkward, these high-speed flexible-belting systems were more practical than the slow-geared schemes of earlier English mills, whose stone structures might or might not be rigid enough to retain the alignment of long shafts and cogwheels. It took a generation for English designers to accept "running a cotton mill by a 'strap.'"

Direct drive came to a symbolic end at Fall River in about 1895. In 1880 that town had led the country in textile output, its spindles and looms driven mostly by steam. Earlier it had been the artfully harnessed local waterpower that had brought and moved the mills. By the time of maximum pro-


LET'S GET IT TOGETHER BUCKLE UP
GM

duction the overwhelmed river had become little more than a stagnant cooling pond for the steam-powered mills. Now the final mill was built, its big Corliss engine unmatched in power: it spun 100 tons of belted millwork driving six acres of machines, beginning with a 45-ton main shaft and a 30-foot flywheel almost as heavy. Yet "engine and millwork alike were virtually obsolete when installed."

The end of the road for reciprocating steam was reached in the IRT powerhouse at 59th Street in Manhattan. In 1900 nine giant pairs of angle-compound engines were installed there. About 10,000 horsepower from each pair turned a towering 32-foot flywheel generator. These were the largest stationary engines ever built, their low-pressure cylinders of seven-foot bore. That powerhouse remained in partial standby duty until about 1950, its piston mastodons mainly showpieces in the turbine-powered metropolis of the 20th century.

Hunter did not live to complete a third volume, which was intended to cover the power-transmission revolution. For that he would have entered the 20th century as his title promises. It is to be hoped that his admirable work will find its continuator.

THE COSMIC INQUIRERS: MODERN TELESCOPES AND THEIR MAKERS, by Wallace Tucker and Karen Tucker. Harvard University Press ($20). THE QUEST FOR SS433, by David H. Clark. Viking Penguin Inc. ($15.95; paperbound, $6.95). Conceded: astronomy is the least interventionist of all the sciences. We take the universe as it is—gad, we had better—without even a chance to look around any corner that happens to face us, apart from a few visits to the nearest cosmic suburbs, such as the moon and Mars. How and when we look provide the only opportunity for experimental ingenuity in discovery and the ordering that follows. Such circumstance gives these books a special pungency, yet they might have analogues in any field of modern science.

Both are brief and readable narratives by engaged professionals that give the reader access to all the facets of the astronomical enterprise today, social, personal, intellectual and competitive. The books are sharp case studies drawn from life; they are not comprehensive surveys. The two narratives are strongly complementary, each occupying a distinct viewpoint.

Wallace and Karen Tucker address the key to an expanding science, the opening of new channels for knowledge. They chronicle by interview and analysis the parentage and birth of five powerful new American observatories, one in New Mexico, three in orbit and one in hope of launch (a hope long deferred by the tragic malengineering of booster-rocket joints).

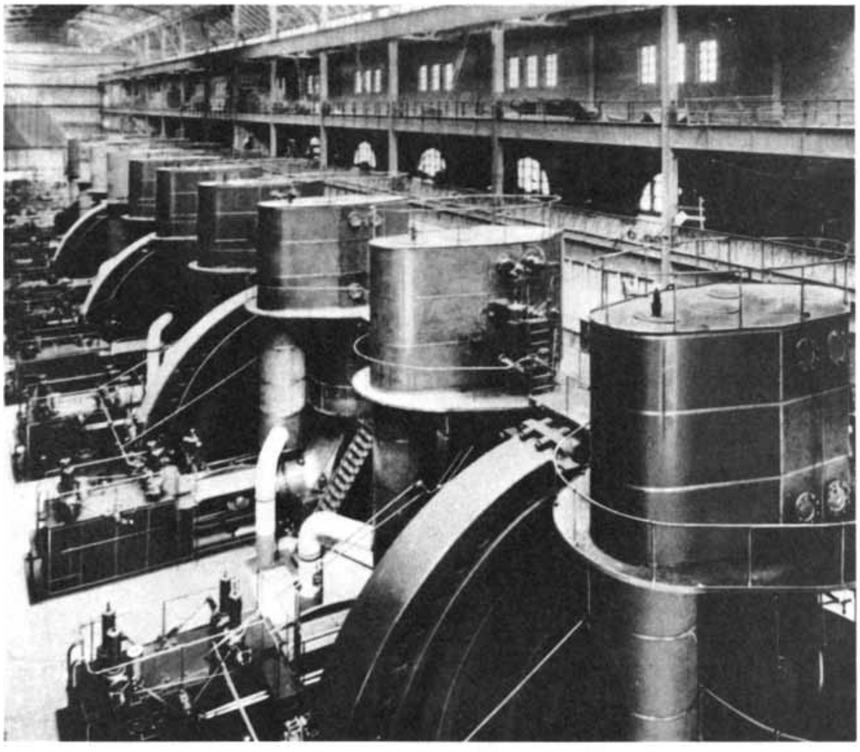
David Clark instead narrates from his own career the steps by which the astronomers somehow characterized a single fascinating and enigmatic object out there, by inspired as well as routine use of an international clutch of existing instruments. One book celebrates new astronomical means and explores something of what they do; the other records a single unriddling that is still incomplete. Each amounts to a backstage visit with the players, some of them popular romantic leads and others in character roles, who walk the astronomical boards today.

The optical telescope on Palomar Mountain can detect a 10-watt light bulb on the moon. The 94-inch mirror of the Space Telescope, now awaiting resuscitation of NASA heavy-launch capability, could resolve a penlight there. The Very Large Array, the striking set of 28 cooperative radio dishes (each 200 tons and more and 80 feet across) that roll from time to time 20 miles or so on surplus rails across the dramatic sagebrush plain just west of Magdalena, N.M., are more sensitive still. They could tune in a small lunar walkie-talkie. The *Einstein* X-ray telescope could winkle out the burst of a single dental X ray. The best infrared telescopes could record the radiation of a rabbit on the moon were it alive and kicking.

The volume names and offers photographs of most of the inquirers we meet, old and young American astronomers, men responsible in one or another degree for the coming into being of the instruments just listed. We then see photographs of four of the instruments themselves: the grandeur of the white flowers of the VLA in a long shot across the plain, and three of the orbiters in preparation for their launches. One device, the Gamma Ray Observatory, two of whose proponents are here, is still in gestation; we see it only in an isometric drawing provided by its proud and hopeful builders.

It is difficult to miss the feeling that we are reading about victorious generals. These are men of peace, all right, but they share the tasks of such leaders. They all but dwell at the conference table and in the committee room, they persuade, they dream, they decide in the face of ignorance and risk, they devise novel tactics against budget cutters and against refractory Nature. There are those as modest as a Bradley, and those as flamboyant (almost) as a Patton. The marvelous contrivances they create are not the work of small groups in one laboratory; costs can rise to a cool billion or more, a measure of the work that was put in by 10,000 technicians and engineers over 10 years of time.

Of course there are heroic occasions



Generator units in New York's 59th Street subway powerhouse, 1902

Taking a close look at polymer technology allows us to create a better future.

Celanese has pioneered liquid crystal polymer (LCP) research. The unique morphology of LCP thermoplastics combines high melt strength and other attributes with low melt viscosity, making our Vectra™ engineering resins especially suitable for extruding or injection molding into intricate shapes—for ultimate use in electrical/electronic, aerospace, automotive or appliance applications.

Optical polymers researched by Celanese are expected to play a vital role in systems for data storage, signal processing and telecommunications. Current key research programs are developing organic polymers that display non-linear optical characteristics, which could provide ultrarapid signal switching and ultimately lead to wholly optical computers of the future and to new polymeric materials such as laser-sensitive media in optical disks.

Advanced polymer research includes new fiber types such as PBI (polybenzimidazole), for use in fire-blocking layers of airplane seats and protective clothing; high-performance organic fibers for fields as diverse as ceramics and biotechnology; and polymer-based membranes for sophisticated separations and as energy-saving alternatives to distillation or evaporation.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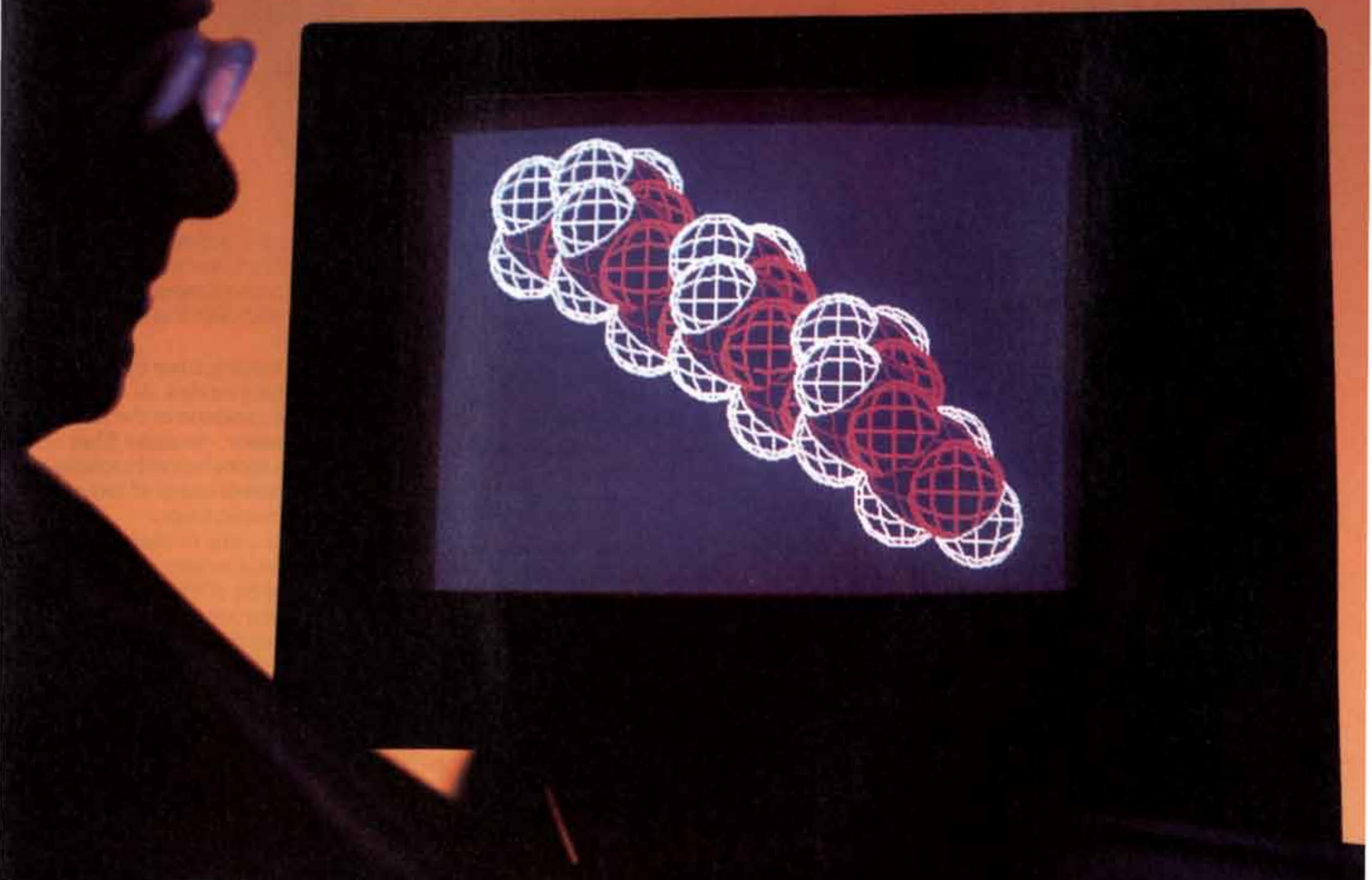
Computer-aided molecular modeling helps provide insights into polymer structure/property relationships.



Close Encounters

Fiber optics: beyond 20,000,000,000 bits/sec.

Summary:

GTE scientists have demonstrated laser modulation and detection at rates as high as 20 gigabits/second. They have developed ultra-small lasers that have light emitting areas as small as 0.2 square microns. They are working to improve the glass fiber itself, as well as to produce optical analogs of electronic switches with the long-range goal of all-optical systems, in which message streams are switched as much as 10,000 times faster than at present.

GTE commercial involvement in fiber optics communications systems dates from the first such installation in Artesia, California, in 1977.

Our scientists developed the system's technology and equipment, and have been contributing to the state of the art ever since.

Current projects deal with increasing the capacity, the versatility, the applications of the systems; longer-term, we are exploring the possibility of all-optical systems.

Faster and faster...

Until recently, optical systems processed digital streams at speeds ranging up to hundreds of megabits per second.

Fast though that may seem, today's carriers are seeking speeds in the gigabits-per-second range. This might even permit the glass to be brought directly to satellite earth stations or microwave towers, for example, for direct conversion of radio signals to light.

Recently, GTE demonstrated the ability to turn diode lasers on and off at rates as high as 20 gigabits per second—about 333% higher than the greatest previously recorded speed.

...and smaller and smaller.

Such speeds require very special lasers. And, as you can see from the electron micrograph at upper right (the head of an ant looking at one of these lasers), it is extremely small.

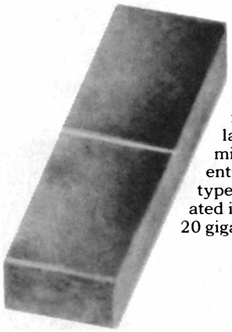
It was constructed on a wafer of InP, by epitaxial growth of a layer of InGaAsP approximately 0.1 micron thick. This was then etched to a mesa shape, and further layers of InP added.

The resulting laser cavity is approximately 0.2 square micron in area, and provides an excellent mate for single-mode glass fiber (fiber with a core of such small diameter that light travels a single path—mode—drastically lowering its dispersion within the fiber).

Switching light with light.

In another project, we are investigating the possibility of ultimately eliminating the electronics altogether by using optical switches.

We are working with materials whose indices of refraction vary with the intensity of incident light—a nonlinear response.



Head of an ant dwarfs a submicron-sized diode laser in this electron micrograph. GTE scientists developed this type laser, and have operated it at rates as high as 20 gigabits a second.

Ultimately, if it actually does become possible to switch systems optically, an improvement in speed of as much as 1,000,000% is theoretically possible.

In its brief history, fiber optics has made astonishing strides. At GTE, we are working to continue at the frontiers of this science—to make fiber optics an even more helpful technique to meet the endless needs of tomorrow's telecommunications.

The box lists some of the pertinent papers GTE people have published on various aspects of fiber optics. For any of these, you are invited to write GTE Marketing Services Center, Department FO, 70 Empire Drive, West Seneca, NY 14224. Or call 1-800-833-4000.

Pertinent Papers

High Frequency Modulation on InGaAsP Lasers: R. Olshansky and C.B. Su, 5th International Conference on Integrated Optical Fibre Communications—11th European Conference on Optical Communications, Venice, Italy, October 1-4, 1985.

140 Mb/s Transmission over 30 KM of Single-Mode Fiber Using an LED Source: L.W. Ulbricht, M.J. Teare, R. Olshansky, and R.B. Lauer, 5th International Conference on Integrated Optical Fibre Communications—11th European Conference on Optical Communications, Venice, Italy, October 1-4, 1985.

Tunable Multiplexer/Demultiplexer: Barbara Foley, John Carlsen, Paul Melman, 5th International Conference on Integrated Optical Fibre Communications—11th European Conference on Optical Communications, Venice, Italy, October 1-4, 1985.

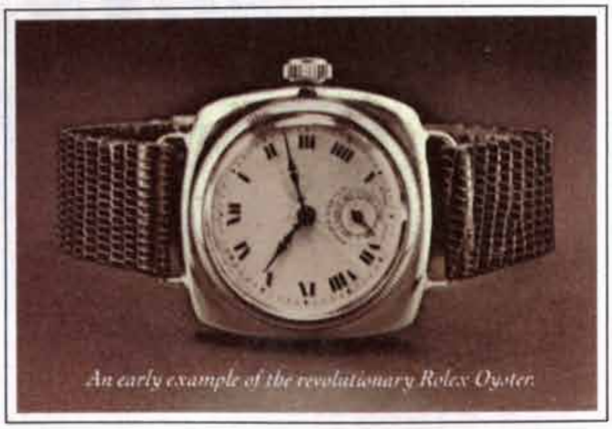
Frequency Modulation and Dynamic Lineshape Properties of Single Mode Semiconductor Lasers—Time Averaged Electric Field Autocorrelation Function Measurements: Elliot Eichen, Paul Melman, William H. Nelson, 5th International Conference on Integrated Optical Fibre Communications—11th European Conference on Optical Communications, Venice, Italy, October 1-4, 1985.

Room Temperature Optical Bistability in InGaAsP/InP Amplifiers and Implications for Passive Devices: W.F. Sharfin and M. Dagenais, Applied Physics Letter 46(9), 1 May 1985.

Time and Wavelength Resolved Nonlinear Optical Spectroscopy of a Polydiacetylene in the Solid State Using Picosecond Dye Laser Pulses: G.M. Carter, M.K. Thakur, Y.J. Chen and J.V. Hryniewicz, Applied Physics Letter 46(9), 1 May 1985.

GTE

The test of time.


An early example of the revolutionary Rolex Oyster.

1914: The Kew Observatory certifies Rolex as the first wristwatch in history ever to outperform the pocketwatch.

1926: The world's first truly water-and-shockproof watch is created when Rolex sculpts the revolutionary Oyster case from a solid block of metal.

1927: Mercedes Gleitze swims the English Channel wearing her Rolex Oyster. Both swimmer and watch emerge in France functioning flawlessly.

1935: Auto racer Sir Malcolm Campbell and his Rolex Perpetual speed to a new world record of 300 miles an hour.

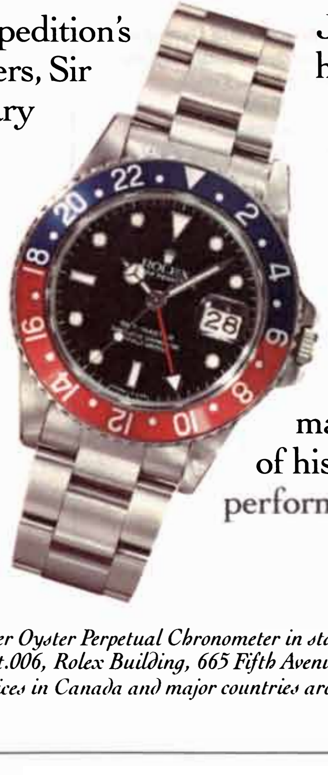
1953: Synchronizing the expedition's teamwork on Rolex Chronometers, Sir Edmund Hillary climbs to the summit of Mt. Everest, the world's highest peak.

1960: Dr. Jacques Piccard breaks the world record with a 35,000-foot deep-sea dive. The Rolex Oyster strapped to his bathyscaphe never misses a minute.

1973: Neither searing heat nor violent sandstorms can stop Tom Sheppard and his Rolex Oyster on their historic Sahara crossing.

1975: Six Comex divers, coordinating their descent on Rolex Sea Dweller watches, reach a record depth of 1,070 feet.

1980: Balloonist Julian Nott times his record 55,134-foot climb on a Rolex Oyster.



1986: Having prevailed in virtually every test of time, the Rolex Oyster marks its 60th year of historic performance.

ROLEX

GMT-Master Oyster Perpetual Chronometer in stainless steel.
Write for brochure. Rolex Watch U.S.A., Inc., Dept.006, Rolex Building, 665 Fifth Avenue, New York, New York 10022-5383. © Rolex 1986.
Other Rolex offices in Canada and major countries around the world.

GMT-Master, Oyster Perpetual are trademarks and disasters on a more intimate scale. Contractors had not carefully enough compacted the sand base laid down in the long desert trenches sheltering the waveguides; as the sand settled, the rf losses grew intolerably. The radio astronomers had to take on supervision of trenching. Detailed engineering control by the scientific designers, its eventual users, seems to have made a triumph of the VLA and of the big X-ray observatory as well; the Space Telescope, where the engineering contractors kept control, has been plagued by technical troubles.

There is a similar story of the detector array of the joint British-Dutch-American Infrared Astronomical Satellite. The engineers of the subcontractor designed the cooled sensitive "retina" and the amplifier layer behind it inadequately. When the element was received, disaster had struck. "A four-million-dollar piece of hardware" about as big as half an index card "with 62 detectors and 62 amplifiers was delivered to the government by the manufacturer and about a third of it didn't work." The damage was done by static charge during careless handling. With a little of the boldness of a Nelson looking at the recall signal with his blind eye, the scientists were delighted. It was "the opportunity to rebuild the focal plane and get rid of those damned MOSFETS." IRAS in operation was a joy; its unprecedented sky catalogue in the deep infrared has shown starburst galaxies by the tens of thousands and the dusty plane around the star Vega, perhaps an unexpected hint of how planets can form.

The trend is clear enough. Enduring big observatories in orbit overpower those below. They must be funded by a consensus, for each one is comparable in cost to all the rest of the expenditures in American astronomy together. "The astronomers of the future" will be like the men we meet here, at once deft politicians, salespeople and tough managers, with a tolerance for paperwork and airport meetings. Yet "they must retain their ability to dream." If they lack that, they will leave, or lose their battles, and the splendid projects will sour over the decade or more of gestation to time-serving bureaucracies without high purpose. Such leadership can be found; it has been found. But there is clear risk that novelty and imagination will fade out as individual responsibility lessens and the more daring maverick researchers lose in the competition for time. The strong director of the Space Telescope Science Institute is a scientist-manager with a luminous record of success in X-ray astronomy from its first days to the largest scale, and yet in his new institute he enjoys the attention of "at least seven advisory boards and committees."

The authors make a terse case for resorting to randomness in an effort to lighten the incessant need for consensus: let some observing time and money go to qualified investigators selected entirely by lot. In Athens too the lottery was seen as a citizens' remedy for dynastic inertia.

SS433 is the 433rd entry in a specialized spectral star catalogue that was published in 1977 by Bruce Stephenson and Nicholas Sanduleak of Case Western Reserve. It was then a "totally unacclaimed" reference list. "One year later, there was not a professional astronomer in the world who had not heard" of it. Yet since then not one other SS object among almost 1,000 has attracted any general attention.

Clark, a radio astronomer of wide interests, collaborating with his colleagues James Caswell and Paul Murdin, really began it all. He tells the story here, very simply and modestly, without photographs of people and instruments, relying on plenty of easy line diagrams of spectra and on simplified models of spinning and double stars. His is a popular narrative of ideas and who had them, of clues and hints and chance meetings, "of false trails, personal intrigue, professional competitiveness, claims and counterclaims,...and, overriding all else, an air of great excitement." The emotions aroused by rivalry and swift success curdled to "disappointment, jealousy, and anger." But no animosity lingers, and the rivals share these pages and these opinions.

The star we now call SS433 was a localized radio feature among some interesting radio clouds, shown to be a possible joint radio and X-ray point source. Clark and Murdin searched for a corresponding optical spectrum with the Anglo-Australian Telescope at Siding Springs. They found a strong emission spectrum that they believed identified it as the right optical object to be the joint source. "The...spectrum is variable; details will be given elsewhere," they wrote casually. Soon variability was confirmed by another group that knew of the SS designation.

How variable? It was Bruce Margon who found that out, a few months after a chance meeting with Clark had handed him "a winning ticket in the universal lottery. He would use his prize well." Margon would study Clark's find from California. What he saw on the plates is now famous. The lines in SS433 were Doppler-shifted, some far to the red, others to the blue. Those shifts were more than 100 times the maximum shift ever before seen in any star of our galaxy. They repeated rhythmically in a few months' time. By late 1979 the catalogue entry was raised to "superstar status" and there it now remains, its shifts displaying motions about a fourth the speed of light.

The theorists have given a pretty good initial model for SS433. It is a spinning compact star with a massive companion. Somehow the spin and the matter the star picks up have generated two relativistic jets that probably spring from the two poles of SS433. Those jets now point toward us and now away as the star gyrates. SS433 resembles a tiny model of an active galactic nucleus or quasar, on a scale of mass down by 10 powers of 10. A deep lesson is being taught us by SS433, we all believe, but just what lesson is lost in whispers. "No model for the origin of the jets" stands out as compelling.

Clark's swift and personal story of the various pathways to the superstar, unique in the galaxy as far as we know, is a little gem of reconstruction. He puts the general reader right into the excitement that ran across the astronomical world as SS433 showed its bizarre emissions to the best instruments on the earth, and filled lecture halls to the walls as we all crowded in to hear about its latest challenge. Clark remains cheerfully excited enough to both open and close his book by saying that after SS433 "the universe could never look quite the same again."

QED: THE STRANGE THEORY OF LIGHT AND MATTER, by Richard P. Feynman. Princeton University Press ($18.50). The bowman knew that light traveled in a straight line whereas his arrow arched in flight. Any mirror broke that rule, although the ray bounce on reflection was orderly and simple enough. The steepening of the ray as light passed from air into denser mediums such as water or glass went a step beyond. The savants could derive all those rules from a single claim, that light traveled along the path of least time. Soon enough there were contradictory findings, narrow slits that spread light broadly and thin films that diffracted light into dazzling colors. No ray scheme at all would work. Mighty Newton himself could not apply his model of corpuscles with any consistency. Only cancellation and reinforcement of waves interfering along many paths could save the phenomena, and the full wave theory, eventually based on Maxwell's fields, ruled serenely.

It was not to last. Wave theories too were done in, by weak light. Radiophysics—a tide of the feeblest of photons, detected only in the aggregate—remains almost pure wave physics;

a change in the frequency produces real trouble. For visible colors every photon detector "makes equally loud clicks as the light gets dimmer," although the photon clicks come less and less often. Light seems irretrievably dual, corpuscle and wave at once.

That puzzle has been resolved in exquisite practice, if not in words, since 1929, by the theory we call quantum electrodynamics, QED, the triumphant prototype of quantum field theories. Now, in four conversational and breezy chapters, with many diagrams and a great deal of qualitative geometric argument, Richard Feynman, who himself gave the theory its most useful and powerful form, undertakes without one equation to explain QED to the generality of readers.

We pay for our present unity of wave and particle by a single grand enforced retreat. All we now try to calculate is the relative probability of photon detection in space and time. We abjure exact predictions. "Yet science has not collapsed." For now the QED rule is general; it brooks no exceptions within all the phenomena of light. It subsumes the entire past, the ray paths and least time, colored films, spreading waves and equal clicks; it governs long-wave radio and ultrashort gamma rays with an equal hand.

Feynman shows that all you have to do to find the probabilities required is to draw and combine a vast family of spinning arrows. They are so numerous because they are sent every which way the light can possibly travel, not just along paths we might expect from a ray model. Each arrow spins uniformly, like the hand of a stopwatch, as it flies along. The rate of turning is proportional to the frequency of the light an arrow represents, 36,000 full turns per inch of path for red light. Combining is done simply by hooking the head of each contributing arrow at any point of detection to the tail of the next arrow until the final resultant arrow has been found.

The arrows start out with length proportional to the square root of the source intensity in their direction, color by color. They shrink as they spin and fly, their length dwindling proportionately to the distance traveled. The resultant composite arrow that takes account of every possible path to any point determines the outcome. The relative probability that a photon will be detected then and there is measured by the square of the length of the resultant arrow at any point, once again reckoning color by color. The weakest and the strongest light are treated in exactly the same way, whatever the frequency.

It is wonderful to follow the construction of arrows appropriate to simple reflection of monochromatic light at a plane mirror. There is no initial concern for equal angles of reflection; the arrows are let fly from the source in any direction that can reach any part of the mirror. But now the combinations are decisive. Most parts of a uniform mirror are not important reflectors, for the combining arrows that come from them point in many directions and add up to little. The bulk of the probability comes in fact from the expected region of reflection close to the equal-angle path, where the arrows are almost fully aligned. The process is not a case of empty cancellation: scrape the mirror coating away just in the places where the contributing arrows have a bias for one direction, and reflection then occurs at an unexpected angle, strong for only one color of light. The mirror has become a diffraction grating, "and it works like a charm." No weighty weapon of mathematics has been used, only a little school geometry and close argument.

The last two chapters go deeper, although they are less detailed. The paradox of interference patterns formed by photons that fall one by one on a screen behind two narrow slits is worked out in a clear way, even to a footnote on the effect of extra detectors that seek out which slit has the photon. We learn how to draw the famous Feynman diagrams, with their electron-photon junctions and their weird and wonderful embroidery of possible interchanges.

There is a secure guarantee of sanity: the electron charge is small, so that the more intricate the diagram is, the greater is the number of junctions along any sequence of alternatives in space and time, and the smaller is the diagram's contribution to the possible interchanges. Simple processes dominate.

The proud inventor tells us of the current state of computation of one fundamental property, the magnetic moment of an electron. That property demands at least one junction, one interaction between field and electron: the electron must, like a compass needle, heed at least one photon to represent the aligning magnetic field. The supercomputers are hard at work (in 1985) taking account of all paths possible that have eight extra junctions, 10,000 diagrams with some 500 choices each. Their total effect is evidently minute, but the experts are after high precision. That result should be precise well beyond the ninth decimal place, for which agreement with experiment is now good. (We miss an account of how it is possible to make such an elegant measurement, perhaps the most precise in all physics; the key to the work is that the moment can be expressed as a ratio of resonance frequencies.)

It is a little sobering that although these fundamental interactions can be splendidly mastered within the step-by-step framework, the scheme cannot yield results for all familiar quantum problems. Any process that requires a very large number of electron-photon interactions, for instance the stationary energy levels of electrons electrostatically bound into atoms, is not suited to the method. This limitation hardly casts a shadow on the theory, for it has been shown that the classical field theory does arise exactly from the diagram framework in the right limit. It certainly does, however, ensure continued use of a variety of descriptive schemes by theorists following differing lines of inquiry.

A final brief chapter includes an overview of the current extensions of quantum field theory into the domain of the quarks. Here are indeed "loose ends" (the chapter is so titled). There are fresh tables and blunt remarks here, not the closer argument that is possible in the simplest case of photons and electrons. Feynman does not glove his opinions; he cheerfully concedes messes and mix-ups in theories beyond QED, although he offers a prognosis of hope.

"Why are all the theories of physics so similar in their structure?" Our guide offers three explanations. It may be that physicists can only think of "the same damn thing, over and over," and have not yet found their errors. It may also be that Nature herself is repetitive. Or perhaps all our theories are aspects of one deeper picture, the grand final theory that has caught many minds. A fourth answer occurs to a reader. The questions we ask by experiment are certainly limited, for example by the averaging over space and time that every instrument must carry out. Perhaps almost every deep structure gives similar answers to the repetitive and approximate questions that so far are all we can ask.

Like a magician, Feynman enjoys misdirecting us with his inimitably slangy patter. Over and over he explains how absurd this theory is. And yet is it? It is unexpected, to be sure, but no more so than least time or waves in coupled electric and magnetic fields. Probably he is joking; in fact, he has here made his QED remarkably sensible, almost Q.E.D. The mathematically fluent will recognize well-known functions and integral methods here in playful geometric disguise, and will accept the treatment of spinless photons and electrons as a stand-in for

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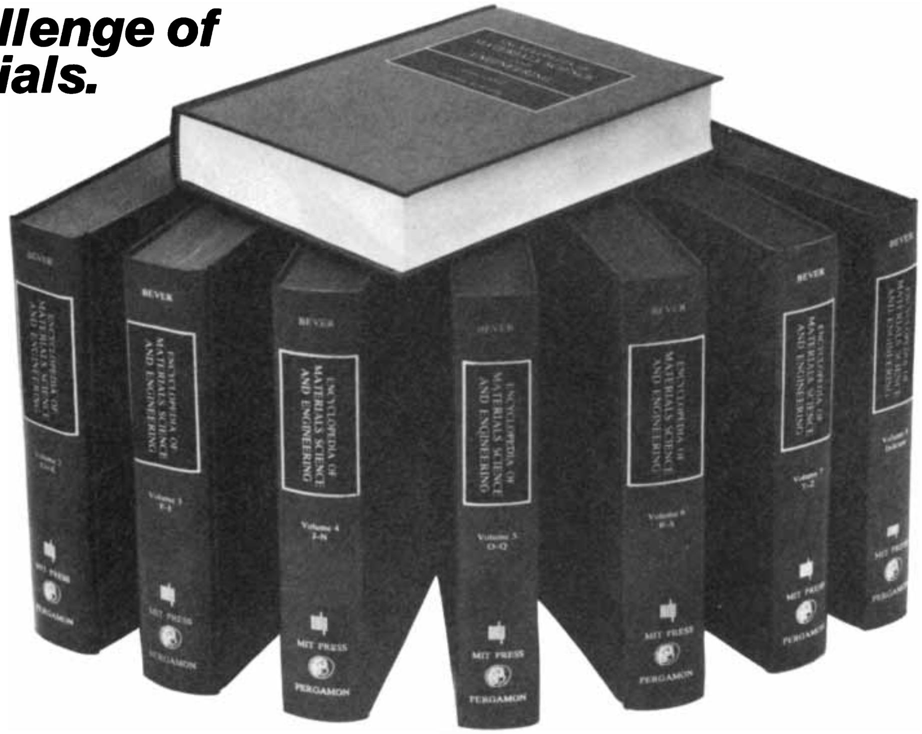

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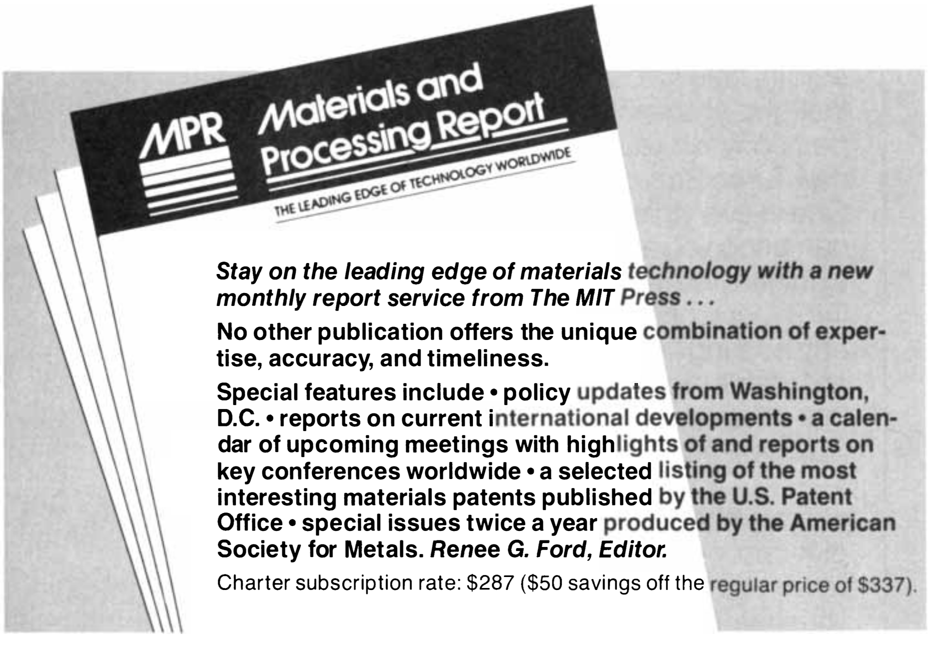

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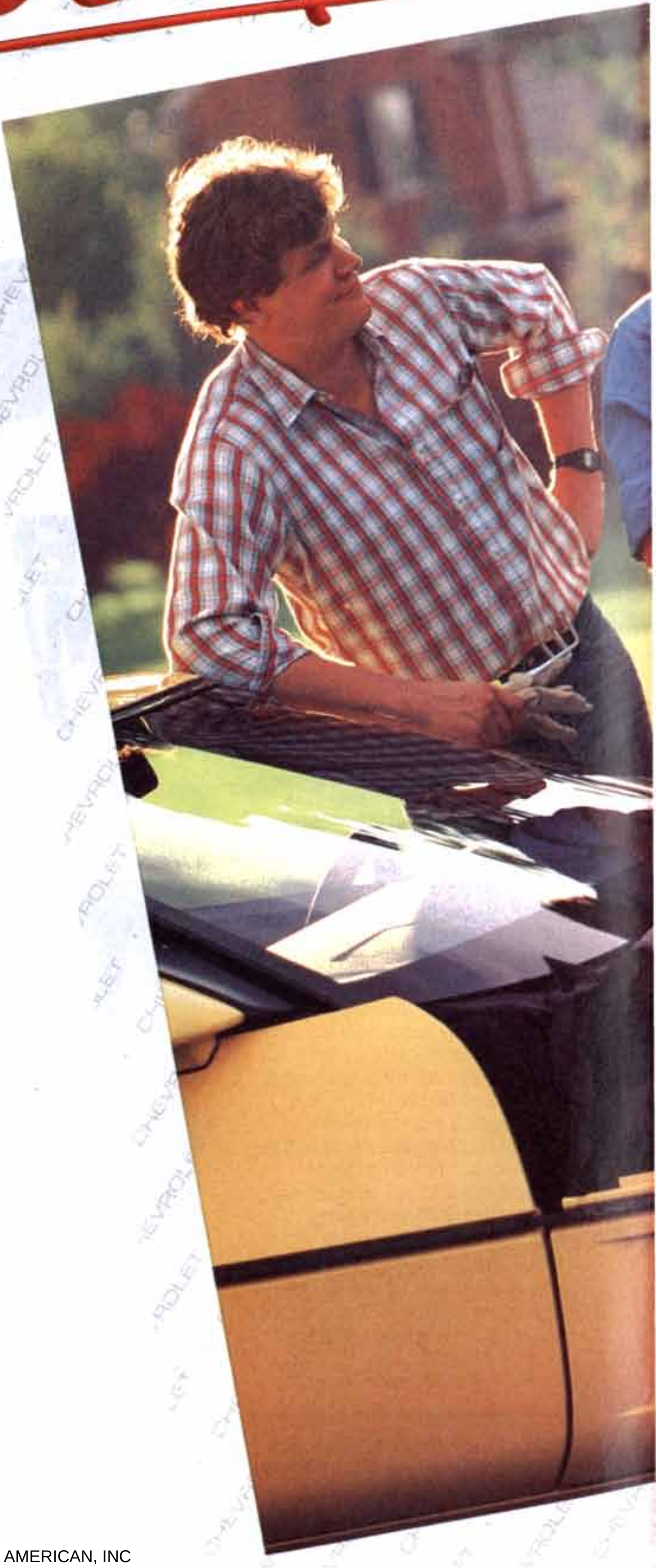


technically more intricate reality. Students of physical science need to read this little book.

The adroit book-midwifery of Feynman's musical friend Ralph Leighton should once again be acknowledged; so should the Alix G. Mautner Memorial Lectures at U.C.L.A., which have their origin in a friendship that goes back to Feynman and Mautner's Far Rockaway years. William Stanton has graced this entire lighthearted enterprise of original pedagogy with his lovely jacket photograph of interference colors.

CLOVER SCIENCE AND TECHNOLOGY, edited by N. L. Taylor. American Society of Agronomy, Inc., 677 South Segoe Road, Madison, Wis. 53711 ($40). This is the centennial year of the classical experiments by two German plant scientists, H. Hellriegel and H. Wilfarth, who showed that the nodules on the roots of the pea were the sources of the nitrogen for the plant's growth. Nowadays in the U.S. the legumes, both the cultivated and the noncultivated, fix about as much nitrogen for crops as does the fertilizer industry, with all its ammonia jets and urea pellets, at an annual rate of roughly 100 pounds per acre of the symbionts.

The clovers of the genus *Trifolium,* their 250 species usually three-leaved (in Ireland almost any three-leaved clover may be dubbed shamrock, and everywhere four-leaved exceptions are regarded as lucky), are the major nitrogen sources of the temperate regions. Alert husbandmen in Europe recognized the virtues of the pealike plants in fallow rotation a long time ago, although clovers were not made crops during Greek or Roman antiquity. The two leading U.S. species, the red clover and the white, have been known for centuries to "contribute towards the enriching of the land," as an English enthusiast put it in 1663. Clover seed was probably brought to the New World unrecognized along with the settlers' hay and bedding.

The fine red clover blossoms have a central tube too long for comfortable use by the honeybee; they do offer a nectar mainstay for big bumblebees. Yet with enough little honeybees a grower can raise a good seed crop of red clover; a couple of hives per acre will suffice, provided more attractive nectar sources are not too close by. Red clover is sown over about a fourth as much area as any of the grain crops in the U.S. The striking plant, member of a distinct genus of legumes, is harvested for hay and silage, easily a billion-dollar crop each year, second in importance to alfalfa.

The sweet white blossoms of the more widespread smaller clover support most of the busy honeybee workers, very effective pollinators of the flowers. White clover is the legume most used in our pastureland; along with grasses, it covers about half of all the well-watered pasture in the U.S., the green meadows and fields set aside for grazing animals over an area as large as the land sown with tall maize or golden wheat. Most of the white clover is never sown by any landowner; the plant volunteers. Its seed is spread effectively by wind, water, birds and the grazing animals themselves. When cattle were first being domesticated, the ancient campsites of the pioneers in western Asia sheltered white clover; "the association of white clover, man, and cattle appears to be natural and mutually beneficial." One American Indian word for the white clover means "white man's foot," although perhaps it was as often the hooves of his cattle.

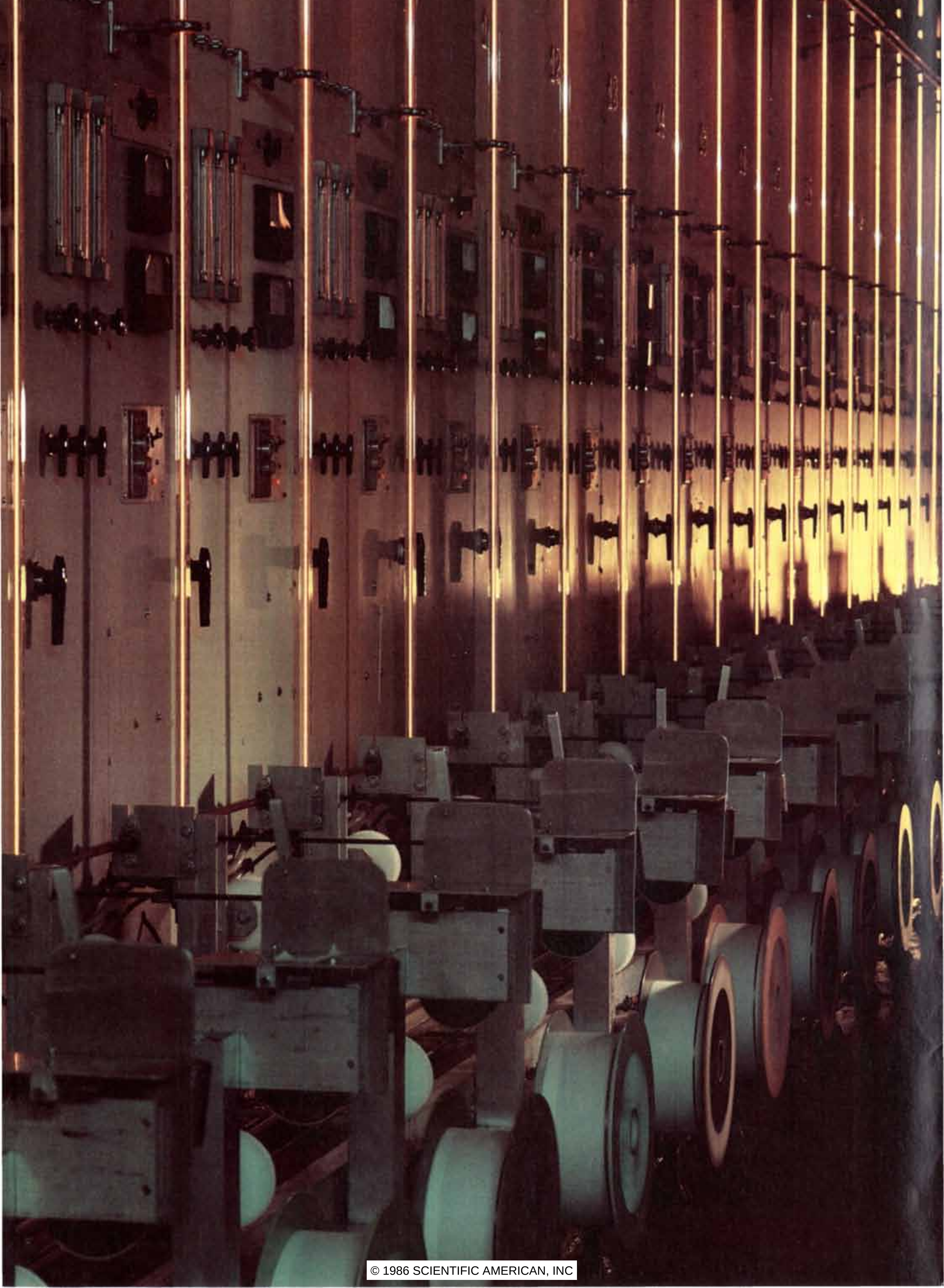
The root nodules where the nitrogen-fixing bacteria dwell were recognized as attributes of clovers and the other soil-building legumes long before their function was known. The farmers knew it was prudent to transfer some soil from a field that had borne successful crops whenever a new clover field was to be seeded. Until the 1930's that empirical result was more dependable than the introduction of laboratory-grown cultures of the bacteria. The symbiosis is a delicate collaboration; bacteria and host are elegantly adapted, strain by strain. There is no way even now to know whether a strain of *Rhizobium* will fix nitrogen and aid its clover host except by direct infection and trial growth for a month or two. Nodule count is a naive measure; indications are that the more nodules there are, the less the plant benefits. Nowadays many forms of inocula are available to use with clover seed, from a moist peat-base mix to an agar slant. The chapter that reviews the symbiosis describes propagation as a craft, not yet as a scientific procedure.

Yet the tone of that chapter is full of hope. "The future for the...geneticist is exciting and challenging." Many strains of the tiny white rods have yielded large plasmids that contain a good fraction of the total DNA of the bacterial cell. They have been transferred with ease to other bacterial forms. Moreover, the clovers have been regenerated as whole plants in vitro from single cells of wound tissue. Such control of host and bacterium alike may someday lead to a success rivaling that of those clever farmers of long ago who came to understand *The Great Improvement of Lands by Clover,* gaining "wonderful advantage by these leaves and branches."

The subterranean clovers, of which there are three species, have seeds that mature in burrs below the soil surface. Brought to Australia by inadvertence from their Mediterranean home a century ago, they are now the major support of livestock-feed production on dry lands there. They were soon recognized as valuable cultivars when suitably fed with superphosphate, often with supplements of sulfur and molybdenum. The plants both nourish livestock and improve the land. They have become a key part of an ecosystem that covers more than 30 million acres in Australia, and now they are finding acceptance in many other countries. The unexpected introduction of a new living species is manifestly not always a bane.

In this book are assembled more than 25 chapters of all kinds on clovers, from taxonomy to practical management, computer modeling of a crop, weed control, physiology, genetics, diseases and pests of every variety, quality testing, plant breeding, seed production. The book includes six chapters on the main economic forms, and a few more on related species, both annuals and perennials, and the native clovers of the American range. An up-to-date monograph of wide scope, the book succeeds in presenting "a scientific treatment" suited for readers with some background in plant science; it is not meant as a text on how to grow clovers. There are a few attractive color plates, proper to adorn a small celebration of that profound discovery made 100 years ago, and possibly to raise hopes that self-conscious science can match the experience of 50 generations of observant farmers.

One late chapter demands a brief account: rose clover (there is no color photograph) is a new drought-tolerant forage crop of increasing economic importance, nourishing cattle, sheep and deer on California rangeland. Its origin, one of the most recent domestications of a wild species, is one of "those rare instances in which scientists, not farmers, introduced the crop." The work was begun in the late 1940's by the author, R. Merton Love, and his colleagues, with seeds first collected in Turkey by an expedition of 1936. In 1956 one plant of the first seeding of rose clover in western Australia yielded a new cultivar, and that in turn a few others. "To date rose clover has been amazingly free of disease and insect damage. A search of the literature failed to reveal any papers on the subject, nor have farmers or cooperative extension agents reported any in California."



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Advanced Materials and the Economy

Progress in materials science and engineering stimulates the growth of many sectors of the economy. New materials and processes meet the needs of existing industries and give birth to new technology

by Joel P. Clark and Merton C. Flemings

A fundamental reversal in the relationship between human beings and materials is taking place. Its economic consequences are likely to be profound. Historically humans have adapted such natural materials as stone, wood, clay, vegetable fiber and animal tissue to economic uses. The smelting of metals and the production of glass represented a refinement in this relationship. Yet it is only recently that advances in the theoretical understanding of the structure of physical and biological matter, in experimental technique and in processing technology have made it possible to start with a need and then develop a material to meet it, atom by atom.

This issue of *Scientific American* explores the new field of materials science and engineering and the new relation between materials and society. It consists of two assemblages of articles. The first group explores the economic demands and policy considerations that shape demand for materials in the U.S. and other industrial economies. The second group presents overviews of the principal segments of materials science and engineering, explores the capacity of investigators to meet the needs outlined in the earlier articles and maps the trajectories that further inquiry is likely to follow.

Collectively both groups of articles make a highly significant point. In addition to meeting needs, materials science and engineering creates opportunities and provides society with new ways to address such problems as the scarcity of resources, the maintenance of economic growth and the formation of capital. Productivity and the structure of the labor force are also profoundly affected by advances in the field. For industrial, financial and governmental leaders the definition and implementation of strategies that exploit opportunities created by materials science is a central challenge of the last quarter of the century.

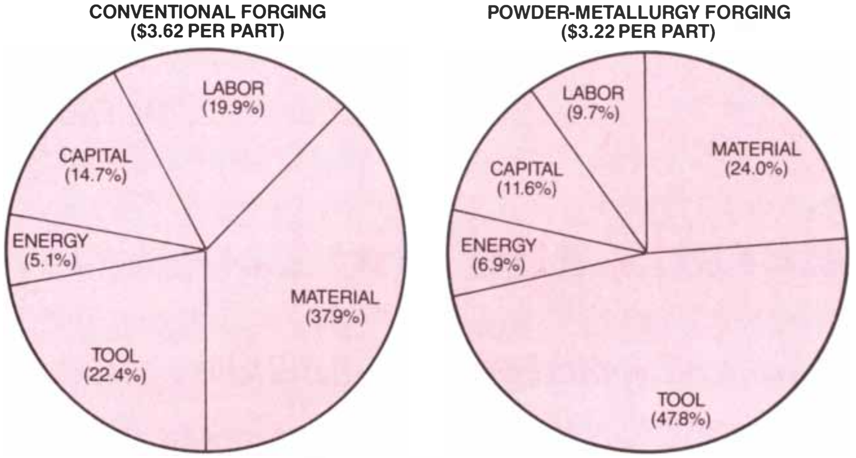
Advances in materials science and engineering have impact quickly throughout the economy. On the average, every person in the U.S. requires the securing and processing of some 20,000 pounds of nonrenewable, nonfuel mineral resources each year. Industries engaged in the direct production of primary materials employ approximately 1.5 million wage and salaried personnel, or about 1.5 percent of the labor force. On each person employed in the primary materials industries depend the jobs of from two to three workers in other sectors.

The value of shipments of advanced materials is about $70 billion, or approximately 14 percent of total materials shipments. The production of such materials occupies about 10 percent of the total labor force of the materials industries. As in the case of employment, the indirect effect of the presence of these materials on the rest of the economy is highly significant. The reason is that advanced materials are not an end product; they are assembled into components critical to the successful performance and operation of such large, complex systems as aircraft and aerospace vehicles, electronic devices and automobiles. Advanced materials are essential to the future growth of these and other industries. In fact, progress in materials science sets ultimate limits on the rate at which key sectors of the economy can grow.

If, for example, the computer industry is to maintain the rate at which its products' information-handling power has increased, ways must be found to circumvent fundamental physical barriers. Beyond a theoretical limit of 100 million elements per memory chip, technologies must be resorted to that depend on quantum effects involving only a few particles, or even on biological models. The burgeoning demand for communications capacity forces the development of ultrapure glasses and other materials for generating and processing beams of light.

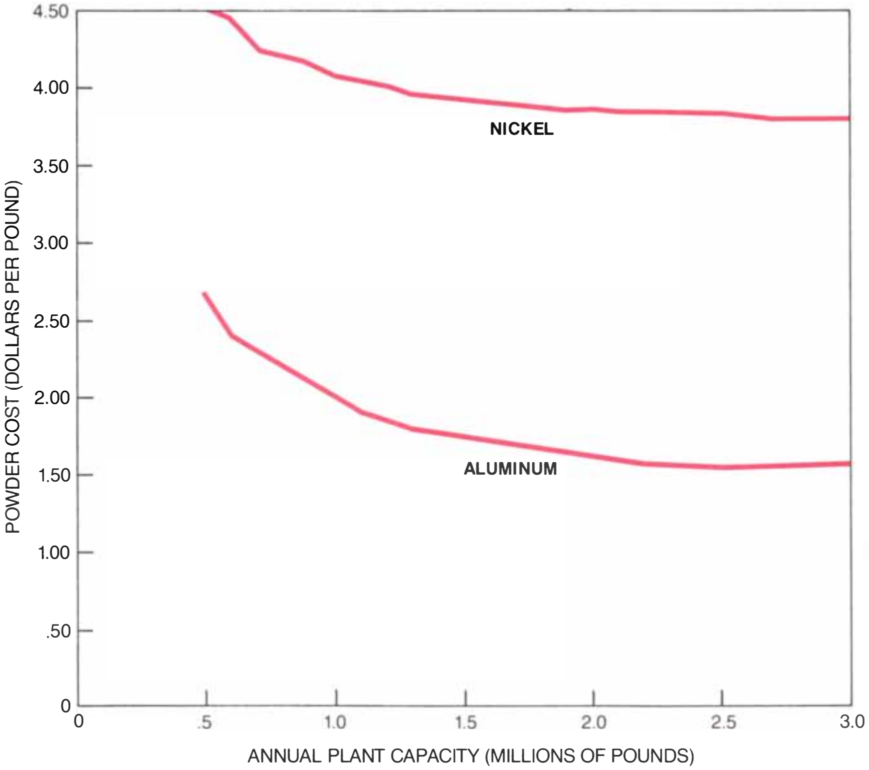
In aircraft and launching vehicles, structural-weight savings can be directly translated into increases in payload (whether of passengers, scientific instruments or warheads) or into fuel economy. To achieve the speeds envisioned for the Orient Express, a Mach

BORON-TUNGSTEN MONOFILAMENTS are continuously reeled from glass tubes in which they are formed by chemical-vapor deposition. The fibers provide high-strength and high-stiffness reinforcement in certain composites, a family of materials that is transforming the automotive and aerospace industries. Each monofilament consists of a sheath of boron on a tungsten-wire substrate. The tungsten is electrically heated to incandescence as it passes through boron trichloride gas, which fills the glass tubes. The gas breaks down, depositing boron on the wire. The production line is at the Avco Specialty Materials Division of Textron, Inc., in Lowell, Mass., the developer of the process.



COMPETITION BETWEEN PROCESSES can influence materials use just as competition between materials themselves can. The charts break down the cost of producing automotive connecting rods by conventional forging and by a new process, powder-metallurgy forging. The mold needed for powder metallurgy costs more than a conventional forging tool, but the new method requires less labor and yields a more precisely shaped rod; less material is lost in finishing. Hence the new process is the more economical one.

8 aircraft that could fly from New York to Tokyo in three hours, materials must be developed that can withstand temperatures of up to 3,200 degrees Fahrenheit. Because high operating temperatures correspond to fuel efficiency, turbine blades and other engine components require progress in the development of composites and advanced alloys. In the automobile industry economies of operation continue to compel recourse to high-strength plastics for body construction, as well as the development of ceramic engine components. New materials originally developed for various fields are found to be of value for repairing the effects of injury on the human body.



COST of rapidly solidified metal powders could drop if plant output increased. The curves show the decline expected in the cost of rapidly solidified nickel and aluminum powders. Rising demand for the powders might come from the aircraft industry: rapidly solidified aluminum might be used in airframes, rapidly solidified nickel in jet engines.

Almost every item of military hardware is manufactured from the group of materials that includes ferrous and nonferrous alloys, ceramics, plastics and composite materials. Moreover, industries vital to the military's need for equipment, transport and support are finding it increasingly important to exploit the properties of advanced materials to enhance the performance of the systems they supply.

Materials science stands as a critical element in the resolution of such fundamental economic issues as the finiteness of resources, the scarcity of strategic materials, the maintenance of economic growth and productivity, the creation of capital and competitiveness in the market. Copper nicely illustrates the first point. Continued demand for this elemental metal has been reflected in the fact that very low-grade ores are still being mined, a supply that is supplemented by recovery and recycling. Yet copper's place as a conductor is now challenged by other metals such as aluminum; electrically active polymers are also being developed. In communications applications copper is already obsolete, its place taken by optical fibers.

The ultimate prospect of an energy famine, currently pushed to the back burner of public awareness by the petroleum glut, will find its resolution in technologies based on nuclear fission, nuclear fusion and solar energy, all of them dependent on advanced materials. Transmission losses will be sharply reduced or even eliminated by superconducting alloys and by the products of powder metallurgy.

Advanced materials offer comparable leverage in the area of such strategic minerals as chromium, manganese, cobalt and the platinum-group metals, which must now be imported. Materials scientists and engineers are now developing new metallic alloys and processing methods for them, as well as ceramics, polymers and composites that require little or no reliance on imported materials and often yield more efficient or cost-effective products. Advanced ceramics are particularly significant in this context. To be sure, the production of structural ceramics involves sophisticated chemical processing methods, and their cost and reliability are uncertain. Yet the solution of such problems would considerably reduce dependence on cobalt and tungsten in cutting and wear-resistant applications and on chromium, cobalt, manganese and platinum-group metals in automotive components.

Nowhere is the role of advanced

materials more critical than in coping successfully with the interrelated issues of competitiveness in the marketplace, productivity and the efficient use of capital. A most significant sector in which this interrelation is being played out is the automobile industry. Automobile manufacturers are finding their market increasingly international and competitive. Both price and the ability to offer a wide range of distinct models are important—market requirements that demand economy and flexibility in the manufacturing process. A number of models must be produced from a few assembly lines in small volumes at a cost that allows competitive pricing.

To meet the challenge manufacturers have begun to adopt the *kanban* ("just in time") inventory strategy, highly automated assembly lines and computer-assisted design. Advanced materials play a critical role because they help the manufacturer to address the issue of cost and to achieve flexible manufacturing, and they result in improved performance.

For example, a set of steel-stamping dies for a fender costs about $2 million, whereas a set of plastic-forming tools for the same component costs about $250,000. For a five-year run of 2.5 million fenders the steel die is the more economical because several plastic-forming tool assemblies would be necessary to make the same number of parts. Yet at the low production volumes favored by contemporary market conditions and strategies, the economics of capital costs make plastic the more attractive material.

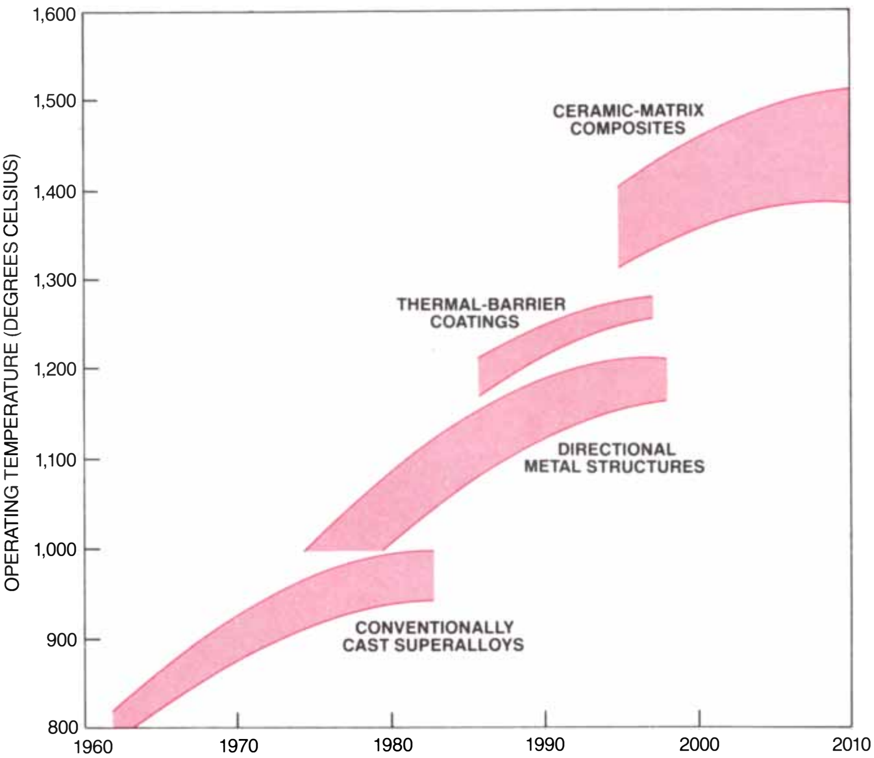
Like bumpers, body panels can easily be formed from polymeric materials. Each of the "big three" U.S. automobile makers is testing the effectiveness and acceptability of plastics for both applications. Ford offers a plastic bumper on certain models of its Escort line and General Motors has two lines with plastic body panels—the Corvette and the Pontiac Fiero. The implications of this shift toward plastic automobiles are sizable. The density of steel is about 7.8 grams per cubic centimeter, whereas the average plastic weighs only about 1.2 grams per cubic centimeter. Switching to the lighter material yields improved mileage. There is another benefit. Because plastics do not rust and are more resistant to minor damage, they extend the life of the average automobile.

Since 1974 the weight of the average U.S. automobile has decreased by 15 percent, or approximately 550 pounds. The bulk of the loss has been at the expense of carbon steel and cast iron. It is paradoxical, then, that although a further weight loss of 27 percent is projected for automobiles manufactured in 1992, steel, as a percentage of vehicle weight, is expected to remain at about the 1974 level. The resolution of the paradox is the use of advanced high-strength, low-alloy steels, which can be fabricated into lighter products than carbon steels can. Concomitantly the use of aluminum has increased by about 50 percent since 1975, to 135 pounds per automobile today, and it is expected to be only slightly higher in 1992.

The substitution of high-strength, low-alloy steel for carbon steel has yielded benefits for both the consumer and the manufacturer. More than a gallon of gasoline will be saved over the lifetime of a car for each pound of carbon steel replaced by the new steels. Consequently the 300 pounds of high-strength, low-alloy steel used in 1986 will result in a saving to the consumer of about 300 gallons of gasoline over the lifetime of the average car. The use of aluminum saves about .6 gallon per pound of the metal, about 180 gallons over the car's lifetime.

The advantage of high-performance materials to the consumer is clear. What is perhaps surprising is that, in this case at least, the higher-performance materials also increase the producer's revenue. The high-strength steels now sell at premiums of about 20 percent above the price of carbon grades, and aluminum sells at a premium of 150 percent—premiums that more than compensate for the reduced tonnage. Plastics, contrary to popular belief, can also be expensive, high-value-added materials. Teflon costs $21 per pound. Vespel, a high-temperature plastic made by du Pont, is priced at about $2,700 per pound. These are significant trends in a materials industry that has matured to the point where the demand for structural materials such as steel has peaked and is largely generated by replacement needs.

Decisions about the advantages of choosing one material rather than another can be framed and made quite precisely in quantitative terms. At the materials systems laboratory of the Massachusetts Institute of Technology one of us (Clark) has applied two such methodological approaches to problems associated with the materials industries. One technique, termed multiattribute utility analysis, enables



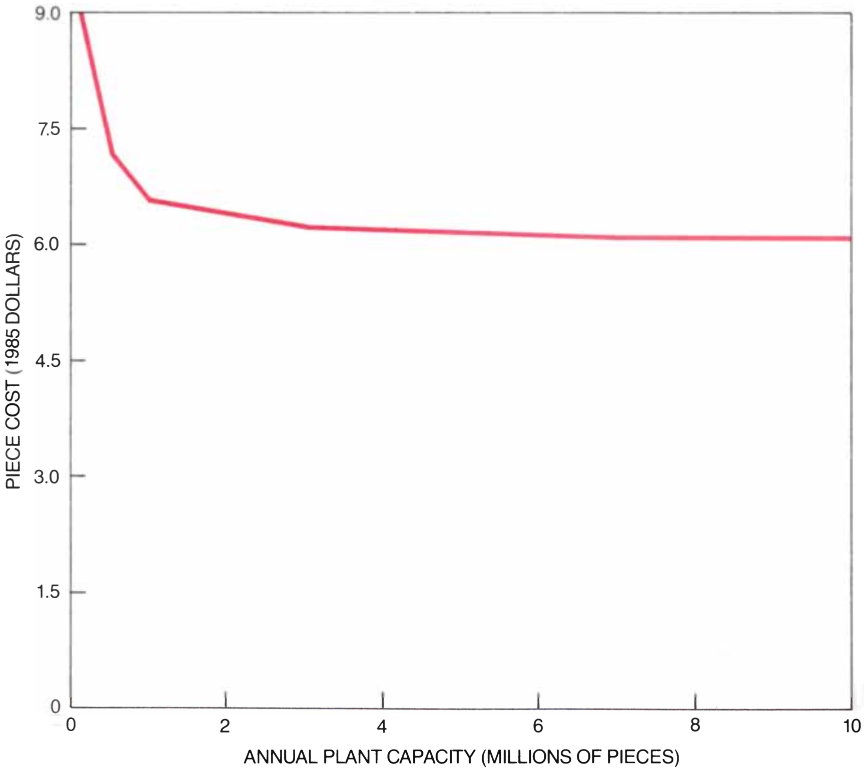
RISE IN OPERATING TEMPERATURE of jet engines (measured at the turbine inlet) will be made possible by new turbine-blade materials. The lowest band on the graph indicates the temperature increase that has been achieved so far through improvements in nickel-based superalloys, the standard turbine material. In coming decades alloy turbine blades made of metals strengthened by directional crystal structures, blades protected by coatings of ceramics or special alloys and ultimately ceramic-matrix composites will allow an increase in turbine-inlet temperatures. At higher temperatures an engine is able to operate more efficiently and burn lower-quality fuels and can generate greater thrust.

	DEMAND FOR CERAMICS (MILLIONS OF DOLLARS) 1985	1995	POWDER REQUIREMENTS IN 1995 (MILLIONS OF POUNDS)
CUTTING TOOLS	55	150-200	1.5
TURBOCHARGER ROTORS	—	40-60	1.0
MECHANICAL SEALS	80	150-200	3.0
AUTOMOTIVE VALVE GUIDES	—	100-200	5.0
TOTAL	135	440-710	10.5

GROWTH IN DEMAND for structural ceramics over the next decade will be concentrated in the areas listed in the chart. The listed applications capitalize on the resistance of ceramics to heat and wear; in addition ceramic turbocharger rotors profit from the light weight of the material, which enables the rotor to reach operating speed more quickly, and mechanical seals benefit from the resistance of ceramics to chemical attack. The requirements for ceramic powder indicated for 1995 assume that each market area will have grown to a size intermediate between the lower and the higher 1995 projections.

the analyst to estimate the value of the characteristics of a material in a specific application. The second technique, process-cost modeling, employs computer models to simulate the cost of producing components using various materials and processing technologies. The models enable the analyst to define the cost implications of a set of assumptions and analyze the sensitivity of cost to changes in such variables as process yields and production volumes.

An automobile engineer could use the first technique to select a bumper material and manufacturing process from a series of choices, all of which meet an engineering performance criterion such as the Federal Motor Vehicle Safety Standards for bumper impact. The choices might be standard forged steel, aluminum or a polymer composite. The analysis enables the engineer to measure the utility of the bumpers according to installed cost versus weight. This analysis is useful because it yields a ranking of the alternative systems.

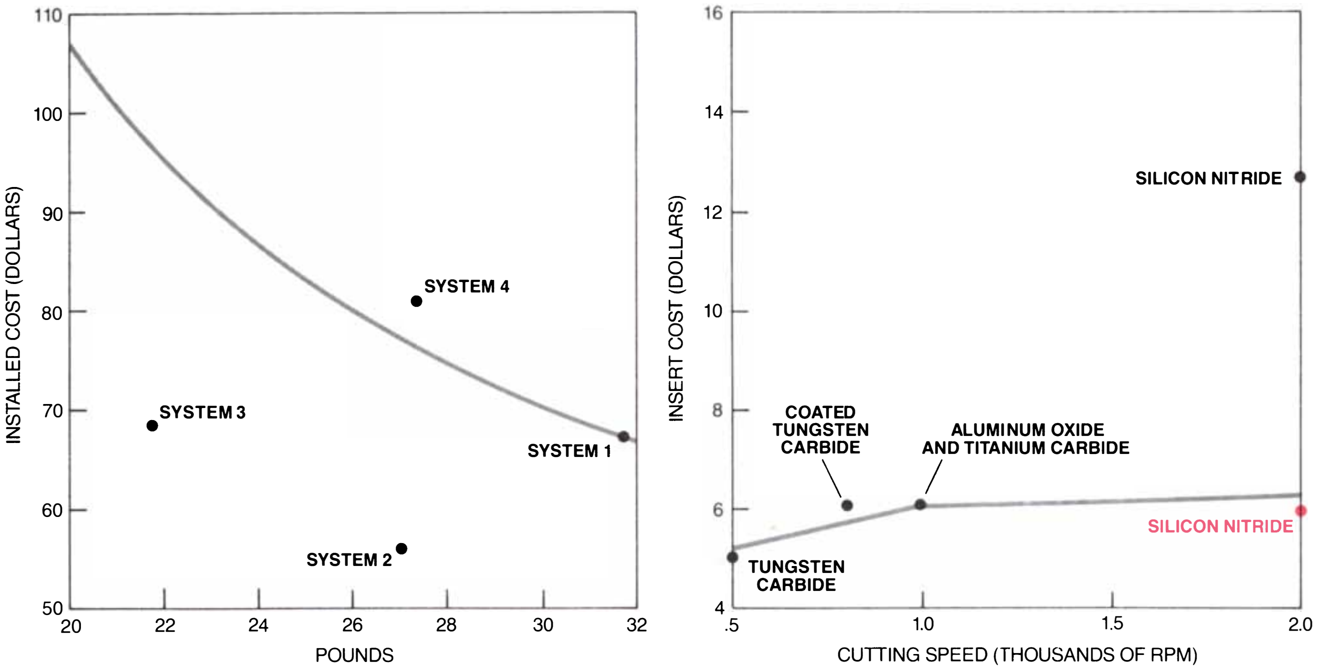


ECONOMIES OF SCALE markedly reduce the cost of injection-molded silicon nitride turbocharger rotors because of the investment required for production. The curve shows the relation of rotor cost to production volume in a hypothetical plant. The yield of the manufacturing process (the ratio of a product's content of a material to the input of the material into the manufacturing process) is taken to be 80 percent (much higher than now); the silicon nitride powder is assumed to cost $10 a pound (much less than now).

Often the competition is less between materials than it is between processes. Most automotive connecting rods, which link pistons to the crankshaft, are forged. In order to reduce cost in the final forming process, certain sections are significantly more massive than they need to be. There is, however, a penalty: considerable material is lost during forging and machining. A relatively new process avoids the difficulty. Called powder-metallurgy forging, it begins with a powdered metal. The powder is loaded into a preshaped form or cast and typically subjected to extremely high temperature and pressure. Because the cast shape is close to that of the finished product, wastage of material is minimized; the process also reduces the need for labor. Yet mold costs are high, which is a problem that should be amenable to computer-assisted design and manufacture.

The competition between forming processes is nowhere more intense than it is in the aircraft-engine market. Here cost is less important than the issue of which process yields a component that most closely meets the specifications. For example, the operating temperature of a jet engine is a key factor in its efficiency. The temperature has increased dramatically over the past three decades, primarily as a result of materials developments. Turbine blades were originally forged. Now they are cast in many cases with special "directionally solidified" structures that result in improved life and high-temperature strength. In the future some kinds of blades will be made using powder-metallurgy and rapid-solidification processes. By promoting the rapid loss of heat from the casting, rapid solidification enhances the tendency of powder processes to give rise to highly homogeneous structures with improved properties.

As a consequence of developments such as these, operating temperatures have been increasing at the rate of about 12 degrees F. per year, a significant figure in view of the fact that each 150-degree increase in the temperature can result in a 20 percent increase in engine thrust and a significant improvement in fuel economy. Whatever the importance of operating specifications, the cost of producing rapidly solidified materials is regarded as being



ISO-UTILITY LINES indicate the various combinations of a component's cost and its performance that would be attractive to manufacturers of plastic bumpers (*left*) and to users of ceramic cutting-tool inserts (*right*). The lines are the product of multiattribute utility analysis, a technique applied by one of the authors (Clark), in which data from interviews with the users of a material are transformed into a mathematical function. In these cases, if the cost and performance of an alternative material system place it below the iso-utility line, it will be more attractive than the current system; if it falls above the line, it will not be competitive. The graph for bumpers plots price against performance (weight) to compare the "utility" of two bumpers now in use (*systems 1 and 2*), both consisting of polyurethane on a steel backup beam but differing in their energy-absorbing systems, with a similar bumper having a third energy-absorbing mechanism (*system 3*) and a system made of a different polymer (*system 4*). For cutting-tool inserts, performance is equated with permissible cutting speed in revolutions per minute. Although silicon nitride makes possible very high cutting speeds, the ceramic will not be competitive until the price per insert falls by at least $6 (*colored type*).

very high. Nevertheless, it is estimated that such materials could be sold at almost the same price as that fetched by conventional powders if an annual production volume of from two to three million pounds in a single plant can be achieved.

Rapid solidification appears to have provided a solution to a major problem in another economic sector. Each year 400 billion kilowatt-hours of energy are lost worldwide as electrical power is delivered to its users. A significant part of the loss is sustained in distribution transformers, devices that reduce the high voltage of the transmission line to the low voltage required in most household and industrial uses. The strong magnetic fields in which the transformer operates set up eddy currents of electricity: random, useless meanderings of current that heat the transformer core. Certain amorphous metal alloys have the wanted magnetic properties for a transformer core but are rather poor conductors, and so they are not good conveyers of eddy currents. Therefore they resist heating and their electrical loss is correspondingly low.

An amorphous metal alloy is one in which the individual atoms assume a more nearly random pattern rather than a crystalline one. Such a material is best made by rapid-solidification techniques. Because the metal cools rapidly, the atoms are caught before the forces among them have time to array them in crystalline fashion. Since 1976 funding from the General Electric Company, Allied-Signal, Inc., and the Electric Power Research Institute has been going into various research and development programs designed to create manufacturing processes for the material and demonstrate its usefulness.

Transformer cores made of amorphous metal have been introduced into the marketplace and are expected to capture a significant share within the next few years. A startling 75 percent reduction in average core loss can be obtained through its use. The importance of the reduction is demonstrated by the fact that conversion to distribution transformers with amorphous-metal cores would save an estimated 40 billion kilowatt-hours per year in the U.S. and 100 billion kilowatt-hours worldwide.

Both economic promise and the necessity for technological progress invite a close look at three areas of materials science: ceramics, composites and semiconductors. Advanced structural ceramics are light and capable of withstanding intense wear and heat. These qualities allow them to be fabricated into components that enhance fuel efficiency, increase productivity in industrial processes and replace materials that are scarce or strategic. Investigators in the field are attempting to overcome two major defects in ceramics: brittleness and high processing costs. Major engineering and economic advantages justify the effort. If ceramics can be successfully used in jet engines, the maximum operating temperature could be increased from about 1,830 degrees F. to as much as 2,700 degrees. Consequently fuel efficiency could be dramatically improved and lower-quality fuels could even be used.

Such opportunities create the potential for rapid growth and profitable investment in markets for advanced structural ceramics in the next five to 20 years. This growth may fall short of the multibillion-dollar estimates forecast in some recent reports. Our own more guardedly optimistic outlook is that the market will approach $1 billion in 10 years. Major applications have been predicted in cutting-tool inserts, turbocharger rotors, mechanical seals and automotive valve guides. Growth rates for areas of current use (cutting tools and seals) will average about 12 percent on an annual basis.

Several technical obstacles will have to be overcome before these markets can develop. Large-scale production must achieve consistency and reliability. Today world production of silicon nitride powder is roughly 250,000 pounds. If the midpoint of the aforesaid 1995 consumption projection for cutting tools and turbocharger rotors holds, the powder requirements for these two applications alone would be approximately 2.5 million pounds, or almost 10 times the current level. A chicken-or-egg problem stands in the way of this target. Producers of raw materials have been traditionally reluctant to invest in production capacity until a market is developed; such large users as the automotive industries have been traditionally slow to adopt new materials until alternative sources and assured supplies exist.

For all four major applications predicted, costs must be reduced if the projected growth is to be realized. Multiattribute utility analysis can be used to quantify the process. For example, it shows that although users of cutting tools will even pay a small premium for the benefits of the silicon nitride insert (up to about $6 per piece, compared with $5 for tungsten carbide inserts), significant cost reductions will still be necessary in order to offer such a price. One set of assumptions that would allow insert producers to sell their products in this price range includes silicon nitride powder prices of from $15 to $20 per pound, an overall processing yield of 85 percent and production levels of at least 250,000 parts per year.

Similar assumptions regarding production rates and powder costs are required if prices for silicon nitride turbocharger rotors are to fall into the range of $14, a necessity if such rotors are to compete successfully with rotors made of superalloy materials. An analysis of costs leads to the conclusion that process yields will need to increase to 70 percent or more (a significant improvement over the current levels of about 25 percent), powder prices must be less than $20 per pound and production levels must be higher than 250,000 parts per year.

Another crucial barrier to the use of ceramics in virtually all structural applications is poor reliability. Ceramics tend to fail catastrophically when cracks that originate from small defects propagate. For instance, the critical flaw size for most ceramics is less than 100 micrometers in diameter, compared with several millimeters for most metallic alloys. There are several methods currently under development to improve the reliability of ceramic components.

Composites are the fastest growing advanced materials. The term composite material refers to a matrix that is reinforced with fibers, whiskers or dispersions of another material. The aim of producing a composite is to have a material whose performance characteristics combine the strengths of each constituent material.

In the past 20 years a number of composite systems have been devised, a familiar example of which is fiberglass-reinforced plastics (FRP). A new class of materials, generically known as advanced composites, is now being developed. (The term advanced composites was coined to distinguish materials incorporating the new high-performance fibers from the rather "low tech" FRP.) Of this group polymer-matrix composites are furthest along in commercialization; there is also much interest in ceramic-matrix composites and metal-matrix composites.

The superior mechanical and physical properties offered by composites compared with homogeneous materials can include a better stiffness-to-density ratio, a better strength-to-density ratio, improved fatigue resistance, greater fracture toughness and good thermal-shock resistance (in the case of ceramic-matrix composites).

Interest in the development of advanced composite materials is guaranteed in the aerospace industry. An improvement in frame weight can reduce direct operating costs, improve payload capacity and increase speed and range. Benefits to both the commercial and the military sectors are therefore great. For several years the aircraft energy efficiency program of the National Aeronautics and Space Administration, in conjunction with the major aircraft manufacturers, has been engaged in a major effort to develop composites for incorporation in airframe structures. Currently only subassemblies made of composite materials have been employed. They include the rudder on the DC-10, the elevator on the Boeing 727 and the aileron on the Lockheed L-1011. All the control surfaces on the Boeing 757 and 767 aircraft will be made of graphite-epoxy composites. The total weight saving of 845 pounds of material will reduce fuel consumption by 2 percent, saving approximately 100,000 gallons of fuel per aircraft per year. In addition composite components are made up of fewer parts than conventional components, further reducing costs.

For instance, it has been estimated that the substitution of a graphite-epoxy composite material for aluminum alloys in a large aircraft fuselage (one that is more than 12 feet in diameter) will reduce the total production costs by 30 percent. The structure would be 30 percent lighter and would exhibit improved fatigue and corrosion resistance. A number of issues, however, still need to be addressed before the various composite materials are accepted on a widespread basis. These include impact resistance, cabin noise and, most important, Federal Aviation Agency approval.

Semiconductors are undoubtedly the most critical family of materials from an economic point of view. The electronics industry in the U.S. alone had an annual aggregate sales value of $172 billion in 1984. Future economic advances depend to a large extent on advances in materials and processes.

The relentless miniaturization of integrated circuits and the irresistible pressures for higher process reliability and lower cost are driving all but the strongest producers from the market. Today the merchant electronics industry in the U.S. (which excludes the major computer and communications companies) is being buffeted by foreign competition, and its very future is in doubt. The merchant industry accounts for about $80 billion in sales. Its loss would be a serious blow to the industrial strength of the country; its future depends on being able to produce advanced materials reliably and economically.

Further progress in this field calls for investigators to plunge into the most profound questions of quantum theory and solid-state physics. Dimensions become so small in the newer devices that surface effects alter electronic behavior in new and often unexpected ways. Topographical dimensions are already being controlled at submicrometer scales and boundary thicknesses within a few tens of angstrom units, a span comparable to that of the wavelength of light. Devices are envisioned consisting of small aggregates of atoms. Reliability in the manufacturing of complex structures must be very high in each of many process steps, and all of this will have to be accomplished in the most demanding competitive climate.

The implications of increased consumption of advanced materials are not all beneficial. As such materials become widely used they may well exacerbate critical economic and environmental problems. The economies of developing countries, many of which are already experiencing extreme pressure from the decline of oil prices, could experience further reduction or even reversal of growth rates as advanced materials replace natural ones. Copper, nickel, cobalt, chromium and manganese are particularly vulnerable. Since countries such as Gabon, South Africa, Zaire, Zambia, Zimbabwe, Brazil, Chile, Peru and Papua New Guinea derive a substantial fraction of their foreign exchange from the export of commodity metals, decreased consumption could lead to problems of global economic and political stability.

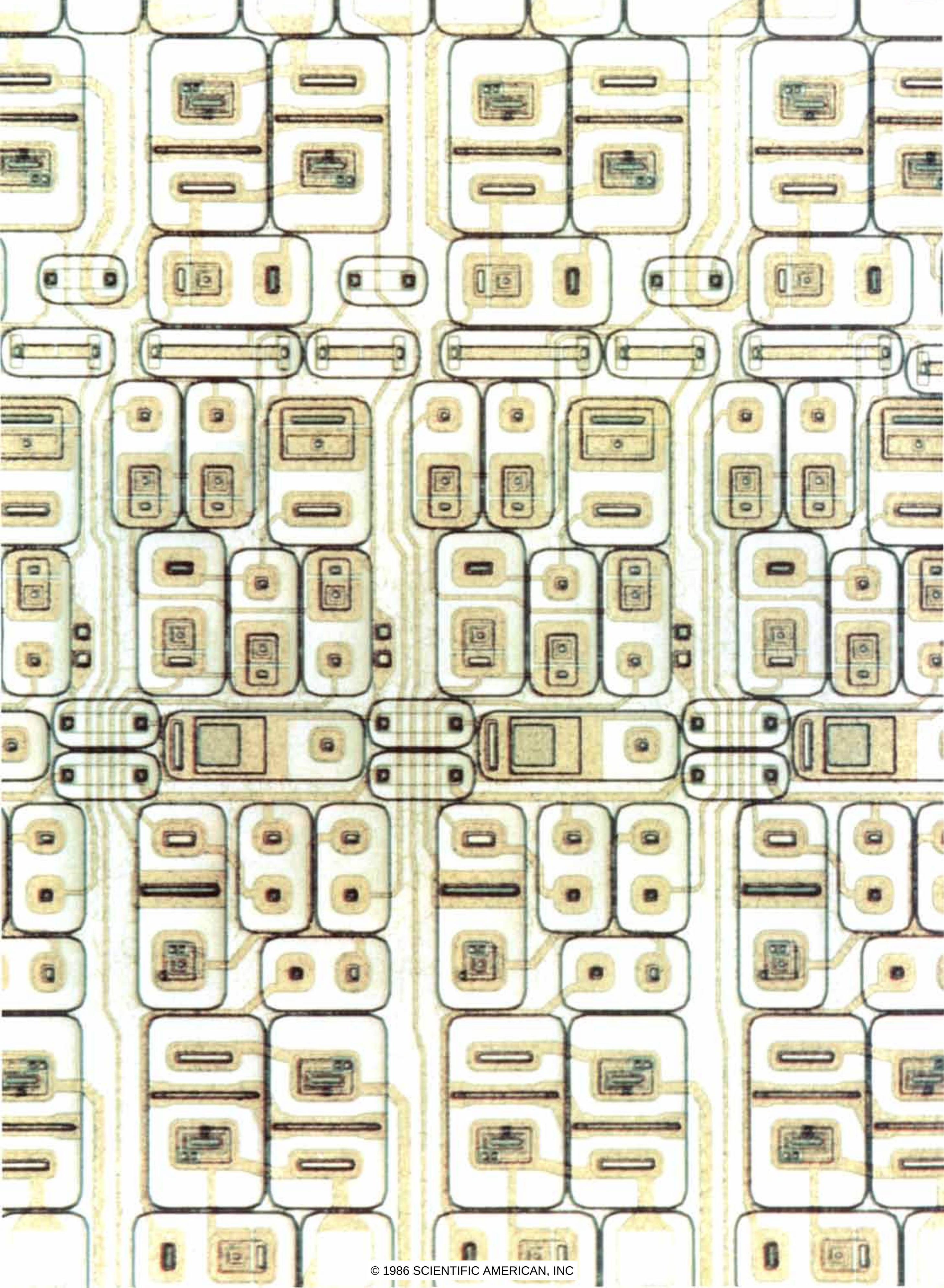
Advanced materials may do little to help industrial society cope with the health hazards and environmental effects of manufacturing. Effluents produced by the manufacture of ceramic powders or organic resins from energy feedstocks are not qualitatively different from those emitted in the mining and manufacture of ferrous and nonferrous metals.

Hazards to health in the workplace may also accompany the production of some advanced materials. The manufacture of ceramic and composite materials may entail the dispersion of particles. Although the carcinogenic effects of these materials on human beings have not been documented, the smallest fibers used in the production of high-performance ceramics have been shown in controlled laboratory studies to give rise to tumors in the lung lining of animals. No regulations have as yet been established to limit exposure to ceramic fibers in the workplace.

The fact that composites may be chemically active in the production stages increases their threat to health and safety. In spite of exhaust systems, spray booths and air masks, some people become sensitized to the vapors and cannot tolerate the environment of a reinforced-plastics plant. Polymers and polymeric composites present special disposal problems. On the other hand, thermoplastic-matrix composites may even be recyclable.

The developments in materials science and engineering described in this article are sometimes the progenitors and sometimes the followers of new technologies. Whether it is creating opportunities or meeting needs, the field of materials science and engineering is in the midst of a widely acknowledged revolution, and one that is certain to be a key factor in shaping the global economy.

TITANIUM COMPONENT of an F-15 fighter's missile launcher is removed from a 600-ton press at the McDonnell Douglas Corporation plant in St. Louis after being shaped at a temperature of 1,650 degrees Fahrenheit. The part is formed superplastically, that is, it is drastically deformed at a temperature below the metal's melting point. Superplastic forming exemplifies the interaction of structure and processing: the metal must have exceedingly fine grain structure if it is to tolerate such extreme deformation.



Materials for Information and Communication

From vacuum tubes to transistors to integrated circuits and optical fibers, the dramatic rise in the power of systems that process and transmit information has depended on advances in materials science

by John S. Mayo

This is an age of proliferating connections: among people, among machines, among silicon chips within a machine, among transistors on a silicon chip. Information is processed by networks of chips and communicated through much vaster networks of copper cables and glass fibers by electrons and photons. There are alternatives to such networks: people can travel to meet one another face to face, and they can process data themselves rather than having computers do the job for them. But in most cases these are poor alternatives compared with what it is now possible to accomplish through electronic and photonic connections. As a result functions once carried out by people are increasingly being carried out by systems of electronic and photonic materials.

The steady rise in the functionality, or functional power, of information and communications systems has depended on progress in materials science. Today's networks of electronic machines and data bases represent a relatively high level of functionality. Before it could be achieved one had first to be able to generate and transmit electrical signals; next one had to be able to control the signals, to amplify and switch them. Each step forward was associated with new materials or processing methods more sophisticated than the last.

Thus in the late 19th century the function of electrical systems was to generate and transmit electricity, and for that simple function only simple materials were needed: iron to support magnetic fields in the generators, copper to conduct electricity and glass to insulate the circuits. At first electric currents could only be switched on and off mechanically (as by a telegraph operator). When the triode vacuum tube was invented in 1906, it became possible to control electricity electronically. To make vacuum tubes engineers had to move beyond iron and copper and master the use of such materials as tungsten and thorium, which served as electron-emitting cathodes.

The vacuum tube was much faster than a mechanical switch. More important, it was the first amplifier. A weak signal in the control electrode (the grid) could control a much larger flow of electrons from the cathode to the anode; the oscillations of the signal were thereby impressed on the larger current. In its role as an amplifier the triode vacuum tube became the foundation of modern radio and telephony, and until the 1950's it was the chief component of all electronic circuits. Yet it had crucial limitations. It required a lot of power in the form of heat, because electrons had to be "boiled" off the cathode; the heat in turn limited its operating life. Commercial systems generally could incorporate no more than a few hundred vacuum tubes without becoming intolerably unreliable.

To build circuits of greater complexity a new device was needed. That device was the transistor, which was invented at the Bell Telephone Laboratories in 1947. It required a million times less power than a vacuum tube (because it did not have to be heated), was considerably more reliable and was a much faster switch. Those properties made it the ideal building block of the digital computer, which was developed at about the same time. As computers and transistors took hold in the 1950's the emphasis in materials research, at least in the electronics industry, shifted to the stuff of which transistors are made: semiconductors such as germanium and silicon.

With transistorized computers the potential for networking electronic components to create information-processing machines had only begun to be exploited. The information-processing capacity of a computer depends in part on the switching speed of its transistors. The smaller a transistor is, the faster it can switch on and off. In the late 1950's the size of transistors decreased dramatically with the development of integrated circuits: circuits in which transistors, resistors, capacitors and the connections among them are fabricated together on a semiconductor chip. Silicon proved to be the most broadly useful chip material, and over the past quarter century much

INTEGRATED-CIRCUIT CHIPS are at the heart of modern information and communications systems. The silicon chip in the photograph is a specialized circuit used in AT&T's most advanced telephone-switching system, the 5ESS. Called a gated-diode switch, it is connected directly to four telephone lines: two incoming lines and two outgoing ones. Hence it must be able to withstand the high voltages needed to ring telephones as well as voltage surges generated by lightning strokes. Resistance to high voltages is achieved by putting the circuit elements on islands of single-crystal silicon embedded in a polycrystalline silicon substrate, and by surrounding each island with a bathtub-shaped moat of insulating silicon dioxide. On the surface of the chip the moats, which are only about four micrometers thick, appear as black rectangles. The single-crystal silicon islands inside the moats are a uniform gray, whereas the polycrystalline substrate outside the moats is mottled. The large islands that occur in pairs near the bottom and top of the photograph are gated diodes. The circuit elements are interconnected by gold-colored aluminum conductors. The chip measures about three millimeters by four millimeters.

research has gone into finding ways of growing silicon crystals that are defect-free and of depositing ever denser networks of circuit elements on a single-crystal chip.

This networking on the microscale has led to an explosion of information-processing capacity—not only because integrated circuits are small and fast but also because they are cheap. The low cost of the silicon chip has enabled it to find application in a wide range of devices and has made those devices accessible to a large number of people. Last year, for instance, an estimated seven to nine million personal computers were sold in the U.S. alone; each one had many times the capacity of ENIAC, the room-size assembly of vacuum tubes that in 1945 was the first digital electronic computer.

The triumph of the integrated circuit has been paralleled by a spread of networking at a higher level. In the not very distant past telecommunication was something that took place only between two people. Now the owner of a personal computer can draw information from data bases around the country, and computers communicate directly with one another without human involvement. The information explosion has triggered a communications explosion.

The desire to communicate large amounts of information has spurred the development of a new technology: photonics. In a photonic system information is carried by pulses of light. The light source is a semiconductor laser or a light-emitting diode and the transmission medium is a hair-thin fiberguide of silica glass. Light pulses (and thus information) can be transmitted through an optical fiber at a rate much higher than the pulse rate of electrical signals sent through a coaxial cable. The first transatlantic optical telephone cable, which is scheduled to begin operating in 1988, will have the ability to carry nearly 40,000 conversations simultaneously; in contrast, the latest coaxial cable, which was laid in the mid-1970's, has a capacity of 10,000 conversations.

Essentially all new long-distance telephone cables in the U.S. are optical ones. Glass is also displacing copper at the local level: optical fiberguides now account for about a third of the growth in the "feeder routes" that carry telephone channels from central offices to clusters of users. Indeed, if it were not for fiberguides, which are much smaller than metal cables, it would sometimes be difficult to increase the number of local channels, since the utility ducts under some city streets are already overcrowded. Light links are even being employed to connect adjacent electronic machines or equipment frames within a machine. In such applications they are desirable for their immunity from electromagnetic interference as well as for their high pulse rates and small size.

The progress of photonics has been remarkably rapid since the invention of the laser in 1958. In that short time materials engineers have developed lasers reliable and durable enough to operate on the ocean floor—the most effective lasers have turned out to be compound semiconductors such as indium gallium arsenide phosphide—and they have found ways of making glass so pure and transparent that a light signal can travel for hundreds of kilometers before it has to be regenerated. For communications purposes compound semiconductors and ultrapure glass are to photonics what iron and copper were to the electrical transmission systems of a century ago, but the materials and the processing methods

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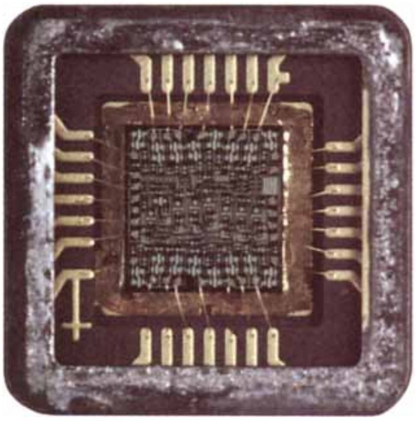

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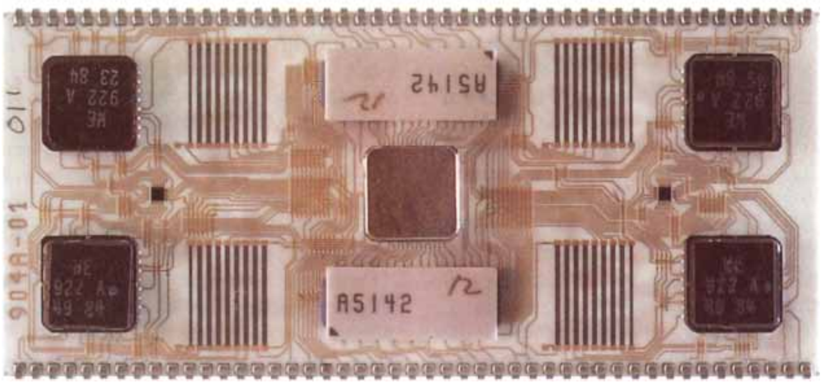

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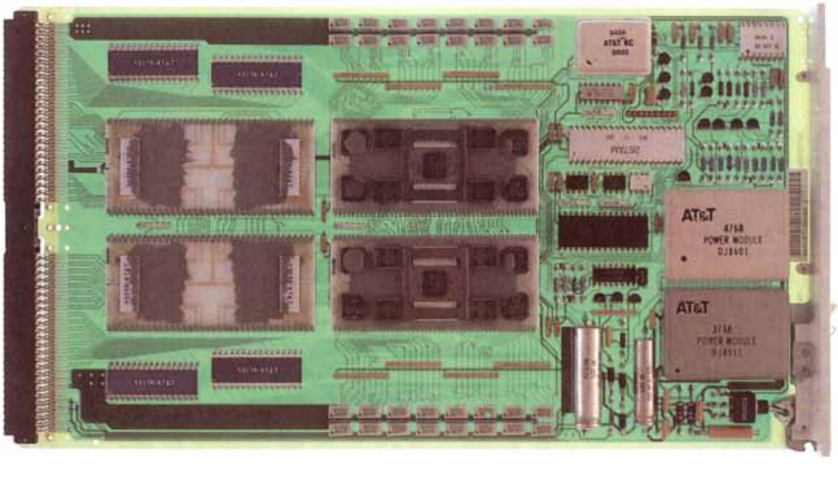


HIERARCHY of interconnections in an information and communications system is illustrated by the 5ESS telephone-switching system. A gated-diode chip is packaged in a ceramic chip carrier equipped with gold leads (*1*). Packaged chips are interconnected by printed gold wiring on a hybrid integrated circuit (*2*), which is also made of ceramic; the insulating properties of the ceramic help the circuit to withstand high voltages. The hybrid circuit is about nine centimeters long by four centimeters wide and carries eight gated-diode chips on its bottom surface in addition to the five visible on the top. Hybrid circuits are interconnected with other components on an epoxy board that has copper wiring printed on both sides (*3*). (Some boards have many layers of wiring.) These photographs and those on pages 62 and 63 were made at AT&T Bell Laboratories in Naperville, Ill.

have grown a good deal more sophisticated since Thomas Edison's era.

Although fiber optics may rapidly supersede electronics as a communications technology, so far the substitution of photonic systems for electronic information-processing machines has been much more difficult to achieve. As yet there is no commercially available photonic control device equivalent to the vacuum tube or the transistor, let alone a photonic integrated circuit or computer. Today if a light signal is to be amplified—the most basic form of control—one must first convert it into an electrical signal with the help of a photodetector (also made of a compound semiconductor), then amplify the electrical signal and finally convert it back into light with a laser. Just as electrical signals could only be controlled mechanically in the days before the vacuum tube, so light signals are controlled electronically in the systems now available.

In spite of its rapid progress, photonics is thus still in a rather primitive state. One of the two main commercial goals of investigators in the information and communications sector is to increase the functional power of photonic systems, in effect duplicating the evolution already undergone by electronics. The incentives are great: a photonic computer, for example, might operate a thousand times faster than an electronic one. But that is a long-term goal. The second and more immediate target is to lower the cost of the functionality that is already available, to make both photonic and electronic systems accessible for a broader range of applications.

The bulk of the materials and the bulk of the costs in a modern information or communications system are accounted for by the simple task of moving electrons and photons from one point to another. In other words, the expense lies not in the components of the system but in the interconnections among them. That is true at every scale from the individual silicon chip to the transcontinental telephone network. It is therefore appropriate to analyze the cost of a typical system in terms of the cost per interconnection at each scale: the cost of the chip or the network divided by the number of interconnections it provides. As one would expect, the longer the interconnection is, the more material is needed to make it and the more it costs.

The aluminum conductors that link circuit elements on a silicon chip are typically only a few micrometers long. They can be deposited by the millions in a single "exposure" through a photomask that defines the wiring pattern. Although the pattern may be enormously complex, each interconnection costs only about 10 millionths of a dollar. Connecting the chip to external wiring, on the other hand, is significantly more expensive. The chip is first mounted on a plastic or ceramic carrier that measures a couple of centimeters across and is equipped with a dozen or more metal leads. The cost per lead of the cheapest plastic chip carrier is about one cent, or 1,000 times more than the cost per interconnection on a chip.

Chip carriers are mounted on a printed wiring board, either directly or by first affixing them to a ceramic device called a hybrid integrated circuit. The cost of a printed wiring board depends on how many layers of wiring it incorporates. In complex systems a wiring board usually consists of eight or so sheets of epoxy-coated fiberglass, each with a copper wiring pattern etched onto it. The sheets are bonded together and connected electrically by copper-plated holes in the epoxy. Such a multilayer board may provide a large number of interconnecting paths, but it is also physically large (in many cases about the size of this page), and so it requires a lot of materials. Furthermore, it is rather hard to assemble and to test. From chip carrier to printed wiring board the cost per interconnection rises by another factor of 10, to about 10 cents.

A wiring board that has been filled with chip carriers (as well as with discrete circuit elements such as resistors and capacitors) is called a circuit pack. A video cassette recorder or a personal computer may contain the equivalent of a single circuit pack, but to build a more complex system a number of circuit packs must be interconnected. The interconnections are often printed on a large multilayer wiring board called a backplane, and the circuit packs are placed upright in a metal frame and linked to the backplane either electrically or optically. The cost per interconnection at the frame level is about $1.

Connections between frames are increasingly being made with optical fibers. This is particularly true when the frames are miles apart in different machines. The cost of such an interconnection is very high, and it rises with distance. A single coast-to-coast fiber link costs millions of dollars—about a trillion times more than an interconnection on a silicon chip. Few users have either the need or the resources to maintain a full-time private connection; it usually makes more sense to rent part of the national telecommunications network.

Because interconnection costs are such a large part of the total cost of a system, hardware designers face two great pressures. The first pressure is to push the complexity of silicon chips to its ultimate limit. The point is not to maximize the number of circuit elements per se; instead it is to put as many interconnections as possible on the chip, where they cost the least. The second pressure is to push lasers and fiberguides to their ultimate capacity, thus cutting the cost of interconnections that cannot be miniaturized.

Since 1960 the number of circuit elements on the most advanced chips has nearly doubled each year. Memory chips incorporating more than two million elements interconnected by about five million conductors are now on the market. Less than three decades ago, before the advent of microelectronics, it would have taken a wireman 10 years to hook up two million discrete circuit elements. A product that once would have been worth 10 man-years is now worth a few tens of dollars, and in the long term its value will fall to just a few dollars.

How far can circuit integration go? A rough estimate can be obtained by dividing the largest practical chip size by the smallest practical transistor size. The limit on the transistor is a physical one. A transistor consists of three adjacent regions on the chip: the source, the channel and the drain. A small voltage applied to a metal gate above the channel controls the flow of electrons (or of positive "holes") from the source to the drain. The three regions are given the desired electrical properties by doping them with impurity atoms. Based on the number of impurity atoms required there is a theoretical limit to how small the transistor can be: no less than approximately 400 lattice constants on a side. (The lattice constant measures the size of a unit cell in a crystal.) In practice the space occupied by a transistor on a chip must be about three times that long. Silicon has a lattice constant of 5.4×10^{-8} centimeter, and so the smallest practical transistor would be $1{,}200 \times 5.4 \times 10^{-8}$, or roughly 10^{-4}, centimeter on a side. Such a transistor would take up about 10^{-8} square centimeter on the surface of the chip.

The limit on the size of a chip is an economic one. Chips are made by slicing a cylinder of single-crystal silicon into about 50 thin wafers and dividing each wafer into 100 or so chips. The silicon inevitably contains microscopic defects, and any chip that ends up with a defect on its surface will not function properly and must be discarded. The larger the chip is, the more likely it is to contain a defect, and so the yield of good chips declines as their size is increased. At present it is uneconomical to manufacture chips whose area is more than about one square centimeter. Eventually the limit can be expected to rise to about 10 square centimeters.

Of that area, only some 10 percent, or one square centimeter, could be filled with transistors on a typical chip; the rest would be needed for interconnections and to isolate circuit elements from one another. With each transistor occupying 10^{-8} square centimeter, there would be room for 100 million transistors (or other components) on the chip. According to this calculation, then, the complexity of integrated circuits can still be increased by a factor of 50 over today's two-million-component memory chips before the limit of silicon technology is approached.

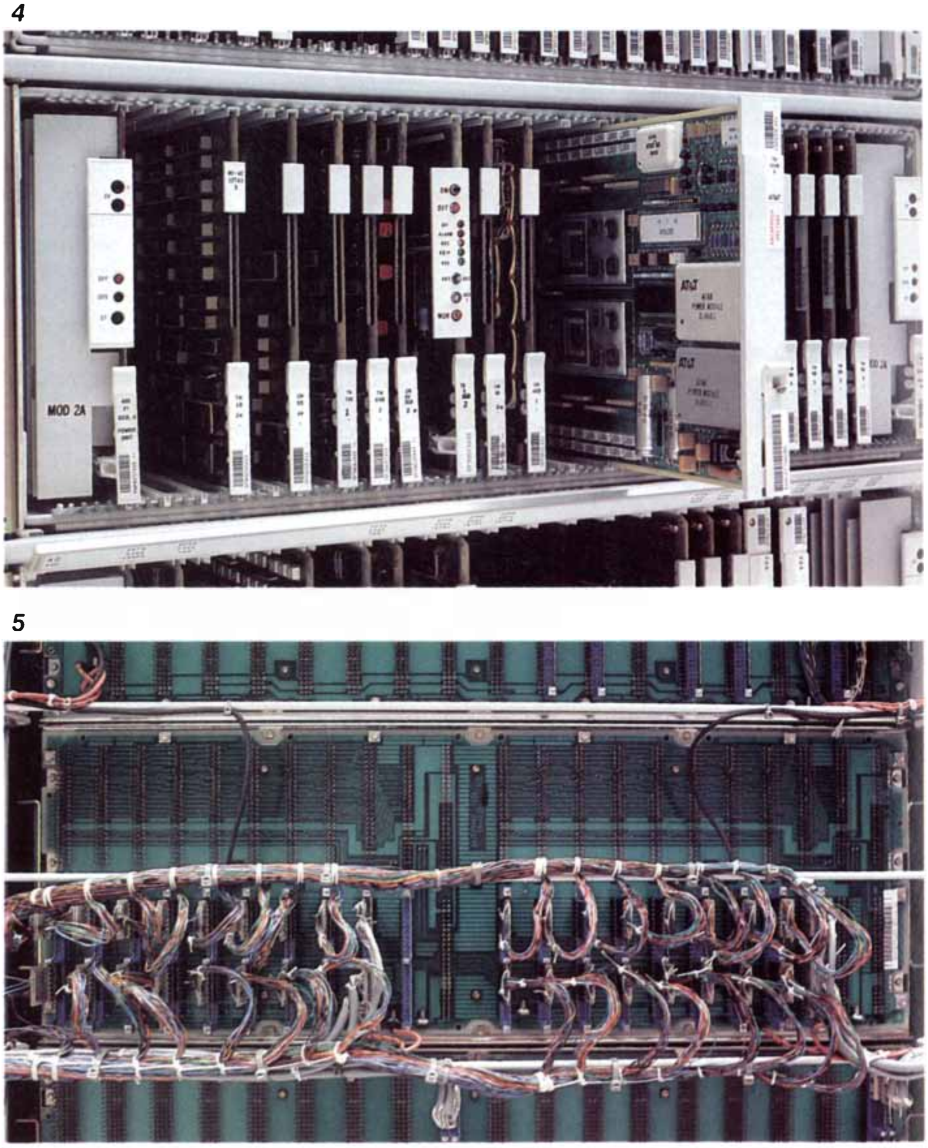
At the current rate of progress the limit will be reached in about a decade. The forecast assumes that investigators will develop new techniques for etching ever finer features onto a chip; some of the promising approaches include the use of electron beams and X rays rather than visible light to define the circuit pattern. At the same time workers will have to make larger chips economical by achieving a better theoretical understanding of the yield-reducing defects in silicon. Theoretical advances, in conjunction with automation of chip factories, should lead to a reduced number of defects.

To move beyond the limits of silicon, investigators will have to turn to other chip materials and chip designs. An example of the former is gallium arsenide, which can support faster if not more complex integrated circuits. An example of the latter is the proposed three-dimensional chip, in which circuit components are arranged in stacked layers rather than only on the chip surface.

Just as one can foresee a limit to circuit integration on silicon, one can also calculate a limit to the pulse capacity attainable with current laser and fiberguide technology. Many factors go into the analysis, including the maximum output power of a laser, the number of photons necessary to define a digital pulse unambiguously given the noise inherent in detectors (the number stands now at about 100) and the extent to which fiberguides attenuate and disperse a light pulse. The result is stated as a product of the pulse rate and the maximum spacing between repeaters. (Repeaters are devices that amplify and regenerate a pulse stream at regular intervals along a fiberguide.) The limit of current technology works out to be 10^{15} pulse-kilometers per second. In contrast, the best research result achieved so far is 20 billion pulses per second, with a repeater spacing of 68 kilometers—in other words, about 10^{12} pulse-kilometers per second. Today's leading-edge system falls short of the technological limit by a factor of 1,000. It will probably take a decade to reach the limit in the laboratory and two decades to reach it in commercial products.

What major improvements will it take to get there? Commercially available glass fibers are already about as good as they need to be; the rate at which they attenuate light pulses is low enough to accommodate most telecommunications projects that depend on fibers. To be sure, a long-term goal is to span oceans with repeaterless optical cables, but that goal is probably beyond the capability of silica glass and may require new fiber materials such as heavy-metal fluorides. As far as glass fiber is concerned the chief demand is for a less expensive product rather than a better one.

Lasers, on the other hand, must be improved in at least two ways if the limit of current technology is to be reached. First, they have to generate much purer light. Although lasers are generally thought of as radiating light at a single frequency, in reality the ones in service today emit several closely spaced spectral lines. Because light waves of different frequencies travel at different speeds, a pulse that includes several frequencies tends to broaden as it moves down a glass fiber; the phenomenon is called chromatic dispersion. If such pulses are transmit-



HIGHER LEVELS OF INTERCONNECTION in the 5ESS are characteristic of a complex system. Loaded printed wiring boards, called circuit packs, are slid onto a metal shelf (*4*) and linked to an epoxy backplane at the rear of the shelf by connectors made of

ted at a rapid rate, and if they are not regenerated along the way by repeaters, they eventually run into one another. The information content of the pulse stream is thereby lost. Hence chromatic dispersion limits both the pulse rate and the repeater spacing. The solution is a laser that emits only a single spectral line. Such devices have been built, and early designs are now becoming commercially available.

Second, at least some lasers must be tunable, like radio transmitters; that is, they must be able to emit pure light not just at one frequency but at a number of selectable frequencies. Tunable lasers would allow a dramatic increase in fiber capacity, because many lasers tuned to different frequencies could transmit independent pulse streams simultaneously over the same optical fiber. This strategy, called frequency-division multiplexing, has long been adopted to raise the capacity of electrical cables. (Time-division multiplexing, in which low-speed pulse streams are interleaved to form a single high-speed stream, is already employed on both electrical and optical cables.)

More important, with a tunable laser each individual light pulse could carry more information than it does now. At present a pulse represents a single binary digit; a high-power pulse stands for a 1 and a low-power pulse (or the absence of a pulse) stands for a 0. If the transmitting laser could be rapidly tuned to, say, one of 32 slightly different frequencies, then each pulse could represent one of the 32 possible sequences of five binary digits. At a stroke the information capacity of the fiber would be quintupled. Lasers capable of this type of quantized digital frequency modulation (FM) will require a new kind of detector at the receiving end of the fiberguide, one that detects the frequency of a signal much as an FM radio receiver does. The existing light-sensitive diodes and "avalanche" photodetectors measure only the intensity of a light pulse.

Reaching the limit of current photonic communications technology will depend also on progress in electronics, because a laser can pulse only as fast as the electronic circuit that drives it. The fastest silicon integrated circuit available today triggers about three billion pulses per second. Semiconductors made of materials from columns III and V of the periodic table are capable of higher pulse rates for the sim-

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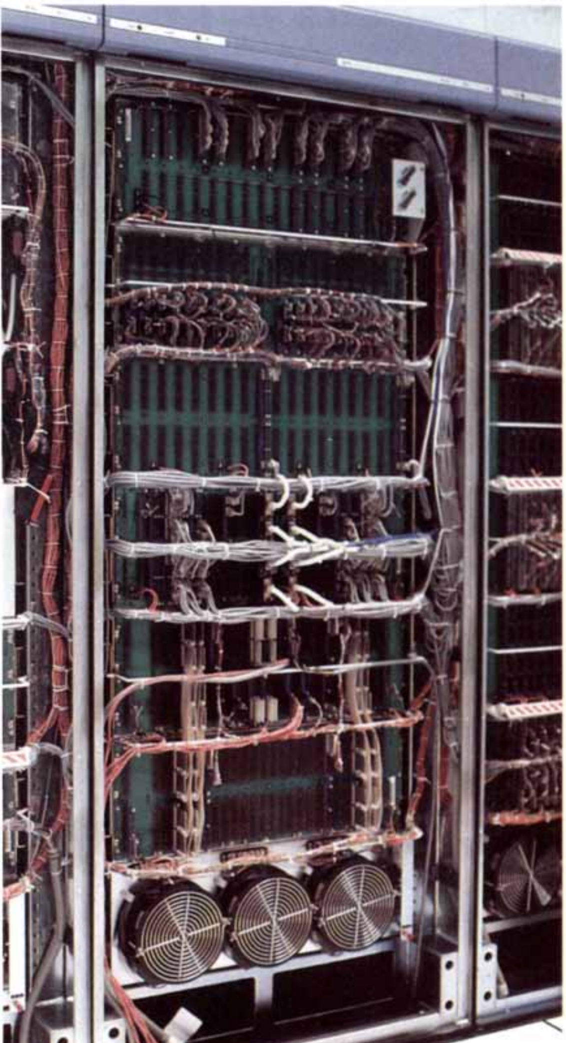

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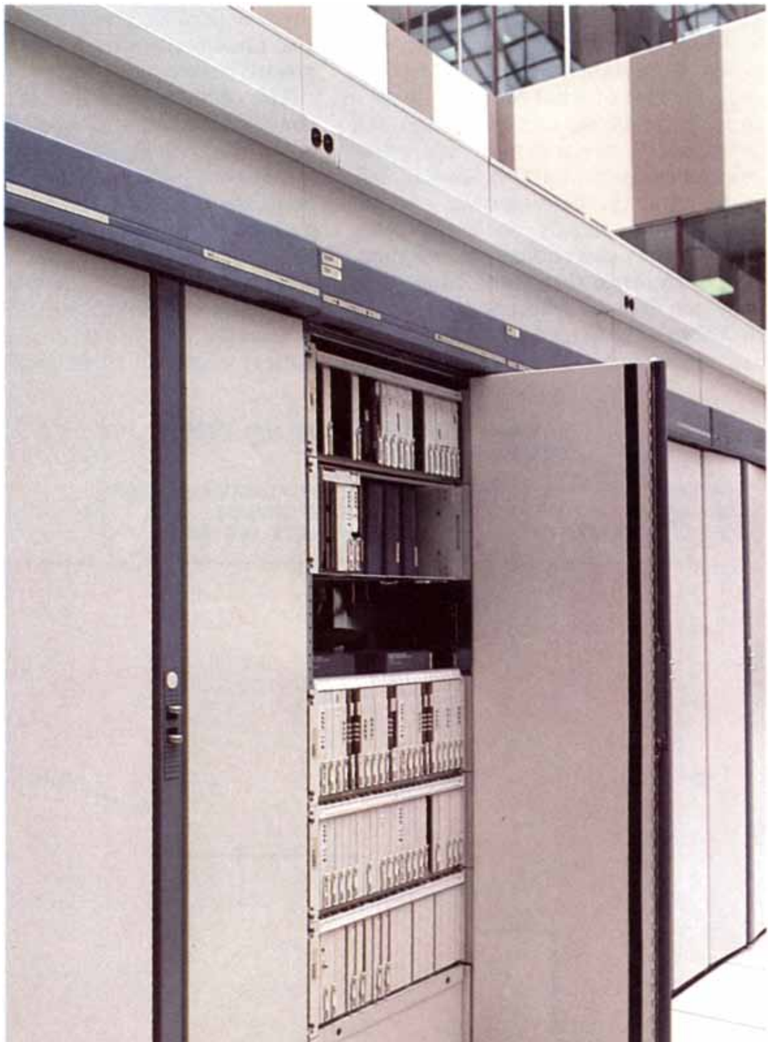


a palladium alloy. The circuit packs are interconnected by printed copper wiring or loose wiring on the backplane (*5*). A number of backplanes are stacked in a six-foot-high frame (*6*), and different frames are interconnected by optical fibers (the small white cables at the center) and by copper wires. A typical 5ESS system (*7*) comprising roughly 40 frames can switch 26,000 telephone lines.

ple reason that electrons move faster in III-V compounds than they do in silicon. Gallium arsenide is the best-studied III-V compound. It has disadvantages that preclude it from completely replacing silicon: for example, it is more subject to defects, which means that gallium arsenide chips are generally smaller and their circuits less complex. Yet wherever ultrafast circuits are needed, as they are in photonic communication, gallium arsenide is becoming the material of choice.

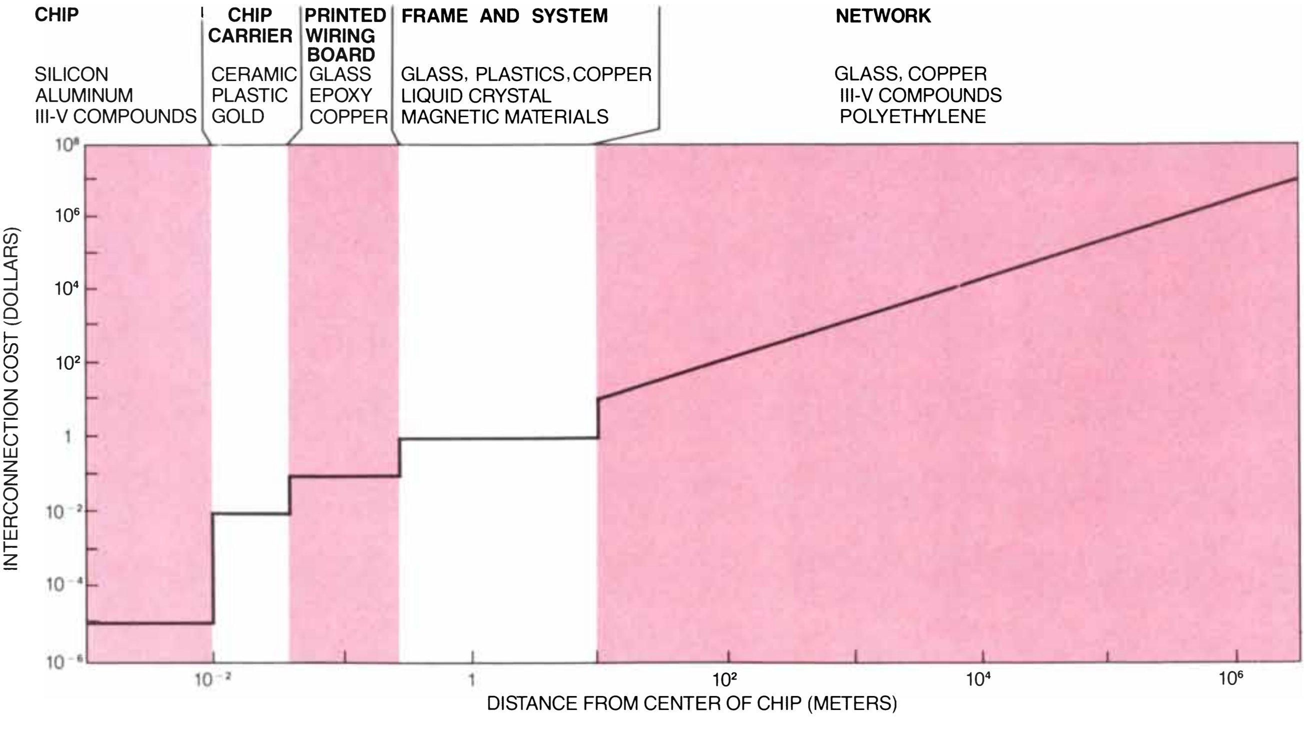
In the upcoming photonics revolution gallium arsenide and other compound semiconductors will play a central role. Lasers, light-emitting diodes and photodetectors are all made of III-V semiconductors; silicon is not satisfactory because it tends to emit and absorb heat rather than light. Indium phosphide, gallium aluminum arsenide and indium gallium arsenide phosphide are among the materials from which photonic devices have already been fabricated, but they are only the first of what promises to be a long series of serviceable compound materials. With modern crystal-growing techniques, notably molecular-beam epitaxy, investigators are not limited to naturally occurring compounds; they can choose the combination of elements they want. Moreover, they can deposit different compounds in alternating layers no more than a few atoms thick. The possibilities created by this engineering flexibility are just beginning to be explored.

In particular, molecular-beam epitaxy shows great promise for creating control devices that switch and amplify photonic signals the way a transistor switches and amplifies electronic ones. Photonics today is strictly a communications technology: signals are generated and transmitted but not extensively processed. Yet the potential information-processing capacity of a photonic computer far exceeds that of any electronic computer. Each photonic "transistor" would be faster than its electronic counterpart; in addition, whereas an electronic transistor can process only one signal at a time, a photonic switch could conceivably handle several signals at once, because several focused laser beams could pass through the device without interfering with one another. The challenge is to develop materials that have the desired optical properties and that are also manufacturable. So far only early prototypes exist.

The first application of photonic control devices will probably come in existing communications systems rather than in computing. A glass fiberguide can carry many signals simultaneously, but in the absence of a photonic signal-processing system it is hard to tap. To remove a signal or add a new one, the entire pulse stream is usually converted into electronic pulses, which are then amplified and regenerated in noise-free form. Next the individual electronic signals are unraveled (demultiplexed), those that have reached their destination are removed and new ones are multiplexed with the "through" pulses. Finally, the combined electronic pulse stream is converted back into photonic pulses by a laser. The process is technically ingenious, but the cost of converting the light pulses into electronic form and back again is high. A photonic processing system would reduce the cost of tapping fiberguides and thereby make it cheaper for many users to share one high-capacity fiberguide.

Given such strong commercial incentives, progress toward photonic control is likely to be rapid. For a decade or so progress can be sustained with known materials, chiefly the III-V semiconductors, but altogether new families of optical materials may emerge from the crystal-growth laboratories. Once photonic control has been achieved, a fully photonic communications network will soon follow; the glass-fiber interconnections are being laid even now.

By focusing on the raw functional power of information and communications systems I have neglected several areas of research that will have an important influence on how pleasant and convenient the systems are for human beings to use. The most obvious example is displays. For all its



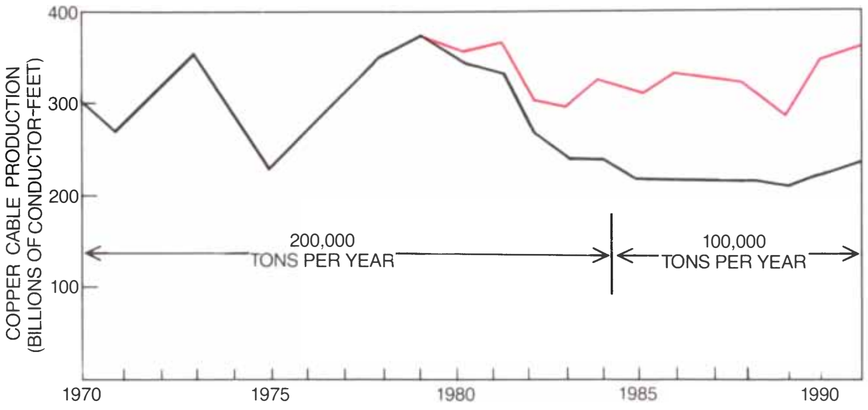
COST OF AN INTERCONNECTION increases with its length. The chart shows the approximate cost and the main materials used at five levels of interconnection. For example, each of the metal conductors on a state-of-the-art silicon chip costs about 10 millionths of a dollar. In contrast, a single optical fiberguide in the long-distance telephone network may cost millions of dollars.

advantages, the cathode-ray tube is a bulky, power-hungry and fragile device. Liquid-crystal displays, the main alternative, are often hard to read, particularly from certain angles. One solution is to have each liquid-crystal display element controlled by an individual transistor or diode. Such a display has better contrast and allows a wider viewing angle, but it costs more.

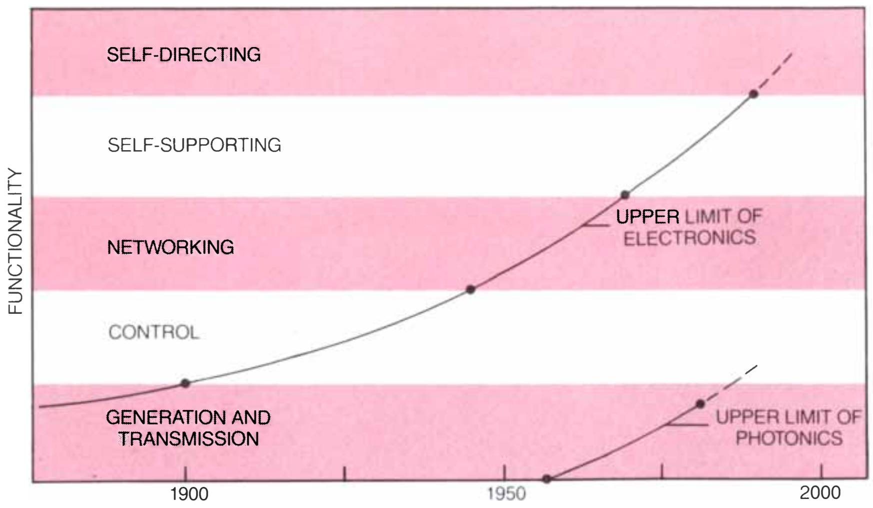
Another area where progress is sorely needed is in systems for storing information. Magnetic disks and tapes have proved to be the best permanent memory devices, but they have rotating parts, and so they use a lot of power and are bulky, slow and noisy. Optical disks, which also have moving parts, have some of the same drawbacks as magnetic disks, although their capacity is much greater. What the world needs is a permanent-memory chip: a chip that has the speed and ease of access of today's random-access memories but that does not lose stored information when the power is turned off. The new device would have to be economically competitive with floppy disks. Magnetic bubble chips, which were once thought to be the solution to the permanent-memory problem, never caught on because the cost of disks dropped as fast as the cost of the bubble chips.

A serious obstacle to the unfettered processing and communication of information is the lack of adequate batteries. The problem is an old one and has only been exacerbated by the flowering of electronic and photonic technology: developments in battery design have simply not kept pace. Devices such as portable computers and cellular radios have substantial power requirements, and a lot of the weight their owners now carry around is in the form of bulky, inefficient and unreliable batteries. If the goal is to connect people to sources of information whenever they need it, and not just when they are near power outlets, then the development of better batteries must be a high research priority.

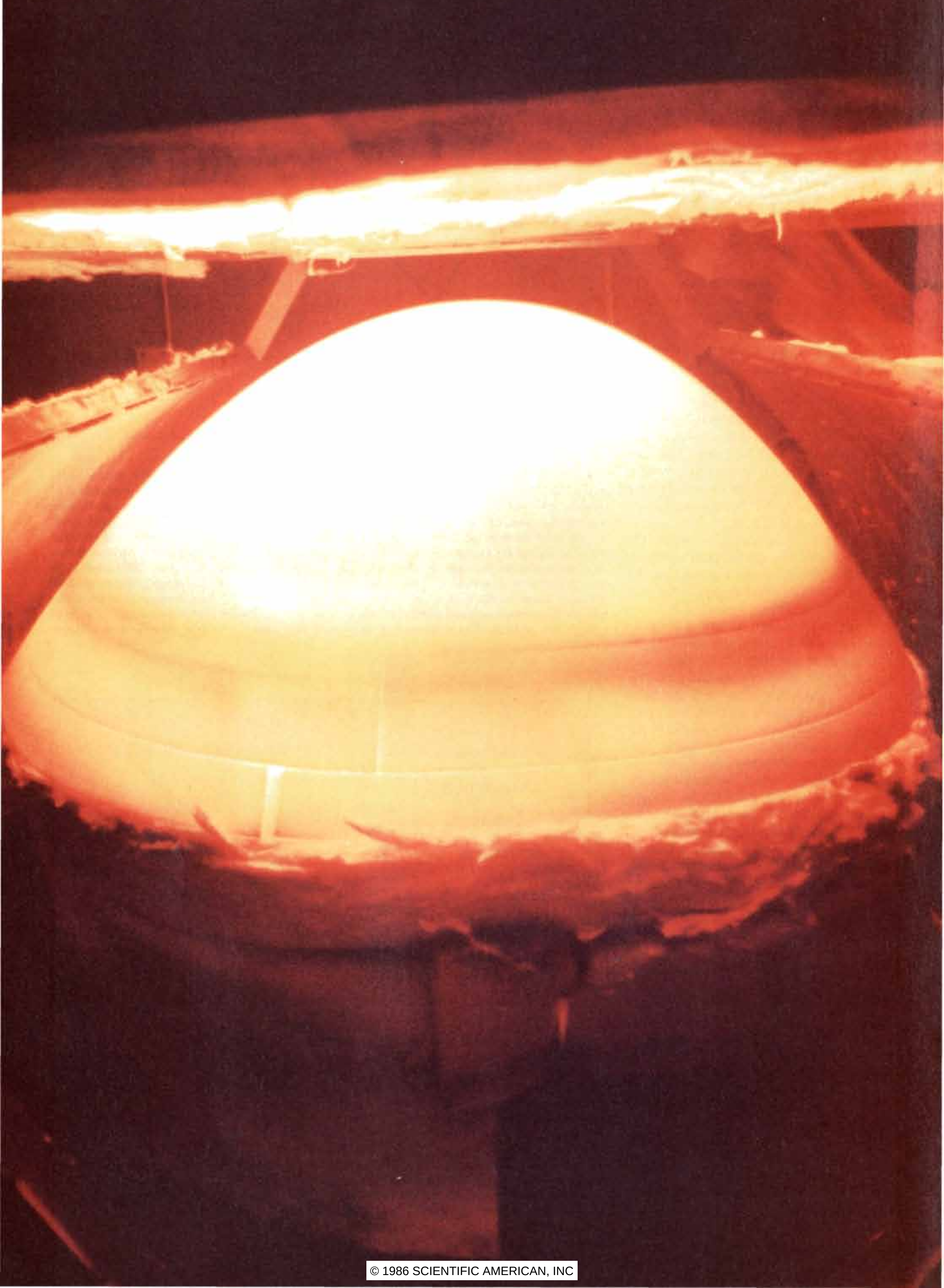
"Interconnect!" would be an appropriate motto for this age of information, which, since connections are made by materials, is in some sense also an age of materials science. Materials science has carried the information and communications industry far and will carry it farther still: to the point at which photonic systems have the functional powers of control and networking that only electronic systems have today. Yet information itself is not material, and materials science has its limits. One of the astonishing features of our age is precisely the extent to which a world of tangible objects—of semiconductors and printed wiring boards, of copper cables and glass fibers, of floppy disks and cathode-ray displays—operates in harmony with a massless world of data, logic functions and software. The higher the functionality of a system is, the more important is its software component. To reach the highest levels of functionality, that is, to build systems that are self-directing and independent of intelligent human beings, is the job not only of materials scientists but also of their partners the software engineers.



GLASS IS DISPLACING COPPER as an interconnection material as photonic communication links displace electronic ones. The black curve shows the annual production of copper telecommunications cable in the U.S. (in terms of the length of the conductors that make up a cable) projected to 1990. The colored curve shows what the projection would have been without the introduction in the late 1970's of optical fibers and of high-volume digital transmission. Between 1970 and 1984 the U.S. telecommunications industry consumed an average of 200,000 tons of copper per year; between 1984 and 1990 consumption is expected to drop by half. Cable production will not drop proportionately because the remaining cable tends to be narrow-gauge: glass is displacing copper from the top interconnection level down. Nearly all new long-distance cables and many new local cables are optical. Glass fibers are also used increasingly within electronic machines.



EVOLUTION of electronic and photonic systems has been characterized by a steady increase in their functionality. The commercial generation and transmission of electrical signals began in the 19th century. With the invention of the triode vacuum tube in 1906 it became possible to control (switch and amplify) signals electronically. The invention of the transistor in 1947 made it feasible to interconnect electronic components in complex information-processing networks. Since the late 1950's, when integrated circuits were developed, the complexity of the networks has risen exponentially. Since the mid-1970's advances in software have enabled some electronic systems to be self-supporting (capable of operating unattended); a few can now be characterized as self-directing (capable of intelligent decision making). Photonic systems have progressed rapidly since the laser was invented in 1958, but so far there are no commercial devices capable of controlling photonic signals photonically. Light signals are controlled electronically, much as electronic signals could only be switched mechanically in the days before the vacuum tube.



Materials for Aerospace

U.S. goals for subsonic, supersonic and hypersonic flight and for space exploration call for alloys and composites notable for strength, light weight and resistance to heat

by Morris A. Steinberg

Early last year the U.S. Office of Science and Technology put forward an agenda for American aerospace activity in the coming decades. The plan established goals for subsonic, supersonic and transatmospheric hypersonic flight. Those goals, together with the Reagan Administration's programs for a space station and the Strategic Defense Initiative, serve as a driving force for extensive improvements in the materials that enable airplanes and spacecraft to function efficiently.

The development of materials, together with advances in the technology of fabricating parts, will play a key role in aerospace systems of the future. Among the materials developments projected for the year 2000 are new composites and alloys for structural members; superalloys, ceramics and glass composites for propulsion systems, and carbon-carbon composites (carbon fibers in a carbon matrix) for high-temperature applications in places where resistance to heat and ablation is critical.

In fabricating parts and structures the main goal is to save weight, thereby increasing fuel efficiency and the distance traveled per dollar spent for fuel. (In 1980 fuel accounted for 55 percent of the direct cost of operating an airline.) Much progress has been made toward fabricating secondary structural parts of advanced composite materials, with demonstrated weight savings of from 25 to 30 percent. Much remains to be done in finding advanced materials that are tougher and at the same time easier to process, so that the cost of fabrication can be reduced. It will also be necessary to evolve new structural design concepts that are specifically adapted to exploiting the major current development in materials science: the increasing capability to tailor materials in order to achieve specific properties. Only in this way will the potential weight and cost benefits promised by the new materials be fully realized.

All these considerations bear on the aerospace agenda put forward by the Office of Science and Technology. The first of the OST's goals concerns subsonic flight. It envisions an entirely new generation of civil aircraft. They are to be noteworthy for efficient consumption of fuel and for attractiveness of price, the aim being to dominate the huge international market for subsonic civil aircraft.

The OST goal for supersonic flight is long-distance efficiency. It calls for the development of aircraft that cruise for thousands of miles at supersonic speeds. They will "link the United States to the farthest reaches of the Pacific Rim." They will also expand the ability of military aircraft to be widely based and to carry out missions over great distances.

The goal for transatmospheric flight is to develop aerospace craft that can take off from and land on conventional runways and fly not only in the atmosphere but also in space, maneuvering easily in and out of each environment. Since no such craft exists now, the task will have to begin with research. President Reagan emphasized the goal of transatmospheric flight in his 1986 State of the Union address, causing the prospective craft to be dubbed the Orient Express because of the possibility that it will carry passengers from the West Coast to Asia in two hours or less.

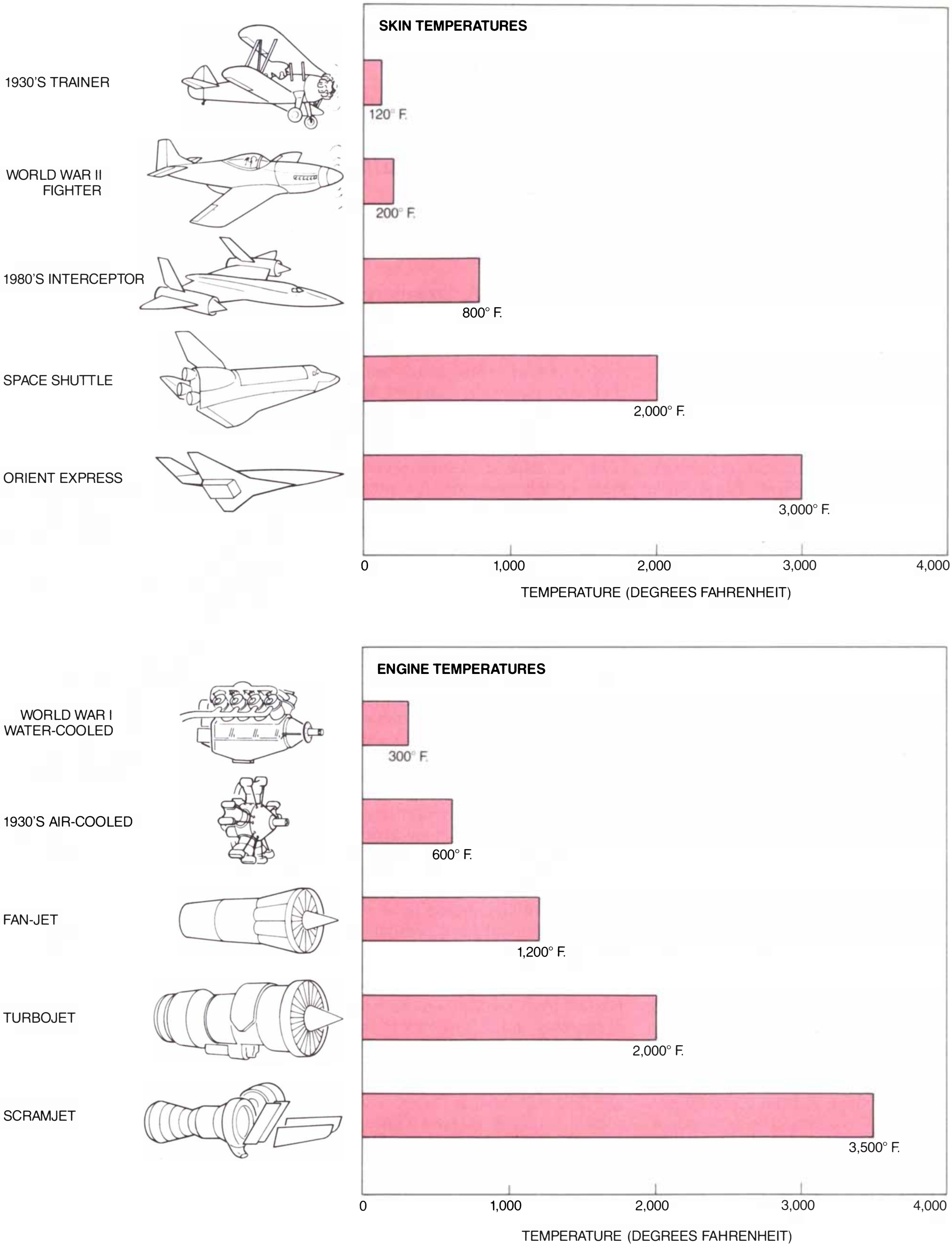
A good start toward meeting the materials requirements of all these goals of the OST has been made over the past few years. Those years have seen noteworthy advances in two fields: synthesizing new materials and employing new composite materials in aerospace structures.

A major new process is the preparation of novel alloys by what is called rapid-solidification technology (RST to materials engineers). The key is extremely fast cooling of the material from a liquid starting phase to a solid phase that is a powder. The rate of cooling can be upward of one million degrees per second. The process gives aluminum alloys higher specific stiffness and strength and alloys based on aluminum or nickel improved temperature resistance. Subsequent machining does not affect the desired properties, and as a result the materials can be made into structural parts by conventional techniques.

Several other new or emerging concepts in processing and assembly are contributing to the improvement of materials. They include superplastic forming, diffusion bonding and "net shape" fabrication. In superplastic forming large changes in the shape of a material are achieved under conditions of high temperature and low pressure. In diffusion bonding the parts are joined at high temperature and pressure. Joining results because atoms diffuse across the solid surfaces being joined; it does not entail the melting that takes place in welding. In net-shape fabrication a powder-based material is formed into a finished shape without the need for further machining. The technique is to compress the powder in a glass, ceramic or steel container shaped like the part.

The new composite materials consist of a matrix, which can be either an

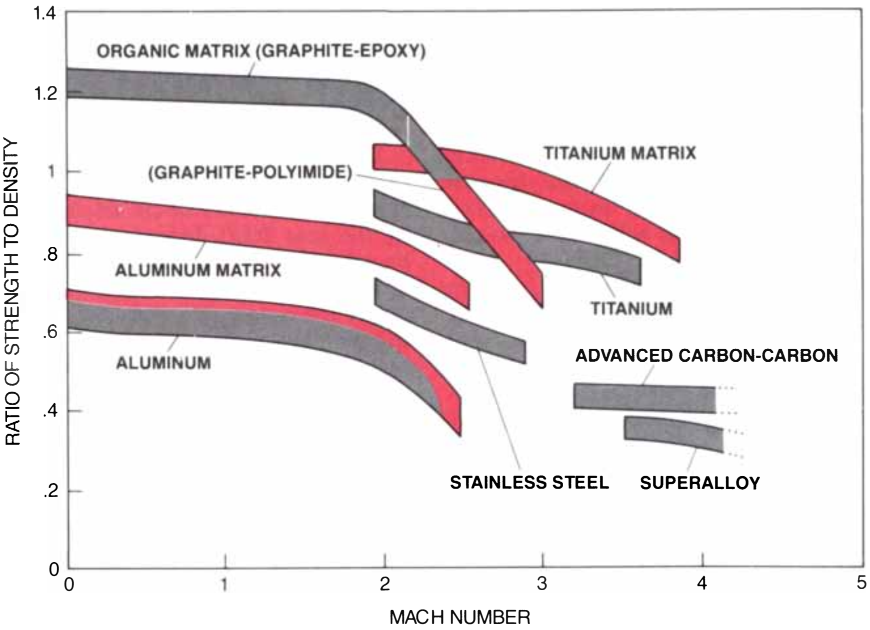
NOSE CONE of the space shuttle exemplifies the use of advanced materials in aerospace structures. The cone is made of a "reusable" carbon-carbon composite consisting of layers of graphite-fiber cloth in a carbon binder with a coating of silicon carbide. It is designed to resist the heat created when the vehicle reenters the earth's atmosphere. The cone has just undergone a furnace test that raised the temperature to 2,350 degrees Fahrenheit.



EVOLUTION OF AIRCRAFT has required continual improvements in materials because increased speed raises the heating of the skin from friction with the air and increased power raises the temperature of the engine. Skin materials have progressed from wood and fabric to advanced alloys of aluminum, nickel and titanium and composite materials based on graphite fibers in a polymer matrix. In engines similar materials have replaced steel and aluminum. The Orient Express is the transatmospheric craft proposed by President Reagan to take off from a standard runway, rise through the atmosphere and cruise at great speed in space.

organic resin or a metal, and fibers of high strength that are embedded in the matrix. The commonest fiber is graphite, but fibers are also made of glass, boron, silicon carbide, Kevlar (an organic fiber) and filamentary metals. The matrix holds the composite together and allows the material to be formed into various shapes. Because of the matrix it is also possible to tailor the material to obtain desired properties such as strength and stiffness. Composite materials are stronger than steel, stiffer than titanium and lighter than aluminum. In addition they offer unique mechanical properties, such as resistance to corrosion and to high temperature. For these reasons they are particularly effective in advanced aerospace structures that must be both strong and light.

Other recently developed materials are aluminum alloys that resist high temperature, aluminum alloys low in density and therefore low in weight, improved ceramics and high-strength steels. Compounds of titanium and aluminum offer low density and resistance to high temperature. Rigid-rod polymers are also new; small rods made of a polymer demonstrating high strength and stiffness are embedded in a tough polymer matrix.



ADVANCED MATERIALS in use or under development for aerospace vehicles are charted according to their strength at increasing aircraft speeds. The gray parts of the bars represent materials now in use, the colored parts materials under development. For aluminum the colored areas represent alloys that remain strong at high temperatures.

An indication of what materials technology has already achieved in improving aerospace vehicles can be seen in its application to jet engines. Over the past 30 years the thrust delivered by a big jet engine for transport and cargo aircraft has increased almost sixfold, until it now approaches 66,000 pounds. During the same period the weight of the engine has increased by a factor of only two or three. The thrust-to-weight ratio of the jet engines being developed for the next generation of military aircraft will exceed 10 : 1; by the year 2000 it may approach 15 : 1.

An example of what has been done is seen in the blades of jet turbines. They were once made of wrought nickel. Now advanced metal alloys shaped by casting are favored. Moreover, they can be made with complex internal passages that provide cooling by air, thereby extending the service life of the blade. The key to this achievement is "investment casting." A wax pattern of the component is coated with a ceramic slurry, which is then dried. Under heat the wax is melted out, leaving a ceramic mold for the part, which is then made by pouring molten metal into the shell.

A major recent development is directional solidification during the investment-casting process. In this process a temperature gradient and a controlled rate of cooling give the blade columnar crystal grains aligned along its major axis. Directional solidification yields major gains in blade life, inasmuch as failure usually starts at transverse grain boundaries (perpendicular to the axis of the blade) and directionally solidified crystals do not have such boundaries.

Another improvement has taken place in blade coatings, which protect the structure from oxidation, corrosion and sulfation from the jet fuel. The new coatings consist of chromium, aluminum and yttrium alloyed with iron, cobalt or nickel. They offer protection at temperatures as high as 2,100 degrees Fahrenheit.

With these improvements and similar ones affecting other aspects of aircraft propulsion, a typical propulsion system today consists of 38 percent nickel, 28 percent steel, 22 percent titanium and 8.5 percent aluminum, along with small amounts of composites, cobalt and ceramics. The improvements can be expected to continue, so that by the year 2000 a typical propulsion system will be likely to contain about 20 percent each of composites, steel, nickel and aluminum, 15 percent titanium, 2 percent ordered alloys (aluminides, meaning titanium-aluminum or nickel-aluminum of a specific composition) and 1 percent ceramics.

Progress in much more than propulsion will be needed to reach the aerospace goals specified by the OST. Further advances in finding new materials and in processing existing ones are crucial. The new generation of subsonic aircraft will need advanced materials for both the airframe and the engines if they are to achieve the desired level of fuel efficiency. Those materials will have to be much stronger, stiffer and lighter than the ones they replace. The materials will also have to offer considerably improved resistance to fracture, corrosion and high temperature.

Aluminum, steel and titanium will probably continue to be the principal materials in subsonic airframes. All these materials, however, will have to be improved. Aluminum alloys with enhanced strength and stability at high temperature are on the horizon. Work is being done to improve the ability of aluminum alloys to resist corrosion and fracture.

One of the alloys of major interest is aluminum-lithium. Its improved properties are based on its lower density. Other aluminum alloys (such as aluminum-iron-molybdenum-zirconium) function well enough at high temperature to be competitive with titanium up to 600 degrees F.

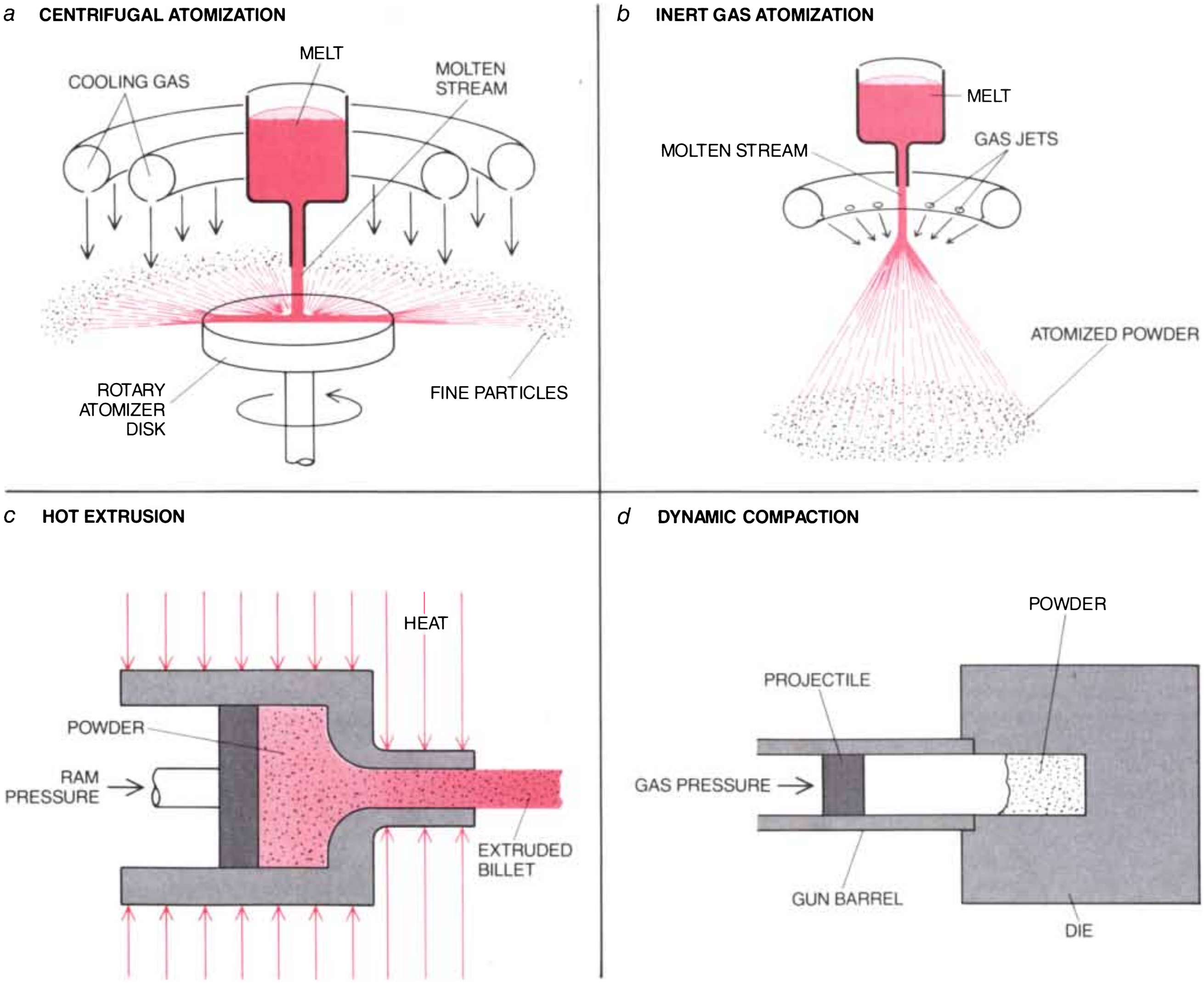
Future steel alloys will be more tolerant to stress and damage without compromising strength or ease of fabrication. Metal-matrix composites also show promise. A material consisting of fibers embedded in, say, aluminum can achieve large benefits in the design of aircraft because of its lower weight, improved strength and greater resistance to high temperature. Such composites are likely to get better with improvements in the quality of the raw materials and in the manufacturing process. Today's titanium alloys usually have to be fabricated at high temperature. Future alloys will be workable at room temperature because of improvements in microstructural composition. That will reduce the cost of making parts from them.

Another development that is having a major effect on aircraft design is the rapidly growing number of parts made of organic-matrix composites, such as graphite fibers embedded in an epoxy matrix. Some 40 percent of the parts of the subsonic aircraft of the immediate future may be made of such advanced composite materials. A new trend is toward thermoplastic composites: fibers embedded in a plastic that can be rendered malleable by heat and that becomes strong and tough after cooling. The composites work well in compression and at high temperature. They also resist damage in manufacture and in service and are simpler to repair than other composites.

The aim of all this work is to have a replacement for the present large subsonic aircraft, such as the Boeing 747, by the year 2000. Indeed, the project has the formal name Transcentury Subsonic Transport. Taking into account the recent and prospective improvements in materials and processing techniques, one can foresee that the new subsonic craft will achieve weight reductions of some 40 percent, leading to significant gains in fuel efficiency. Some of the weight reduction will result because an aircraft designed to take full advantage of the improved properties of advanced materials can be smaller than today's airplanes, in which parts made of such materials often merely substitute for parts made of heavier material.

Saving fuel will be even more important in future supersonic aircraft. A pound of fuel saved in such a craft has twice the payoff of a pound saved in a subsonic one. Many other improvements will have to be made to meet the OST goal for supersonic vehicles. They entail advances in aerodynamics and propulsion, all of which will depend on improved materials.

The requirements in aerodynamics arise mainly from the fact that temperatures on the surface of an aircraft flying at Mach 3.5 (3.5 times the speed of sound) can reach 1,000 degrees F. The air inlets, the outlet nozzles of the engines and the leading and trailing edges of the wings will be critical areas. Advanced metal alloys and advanced composites will be needed to


a CENTRIFUGAL ATOMIZATION

b INERT GAS ATOMIZATION

c HOT EXTRUSION

d DYNAMIC COMPACTION

RAPID SOLIDIFICATION yields a metal alloy in a powder form that is easy to shape and retains its characteristics even when it is subsequently machined. One way to make the powder is to direct a jet of molten alloy at a rapidly spinning blade (*a*). Another method employs directed gas jets (*b*). The powder can then be formed by such processes as extrusion (*c*) and ramming in a shaped container (*d*). In what is called net-shape forming the container is the shape of the part, which then needs no machining.

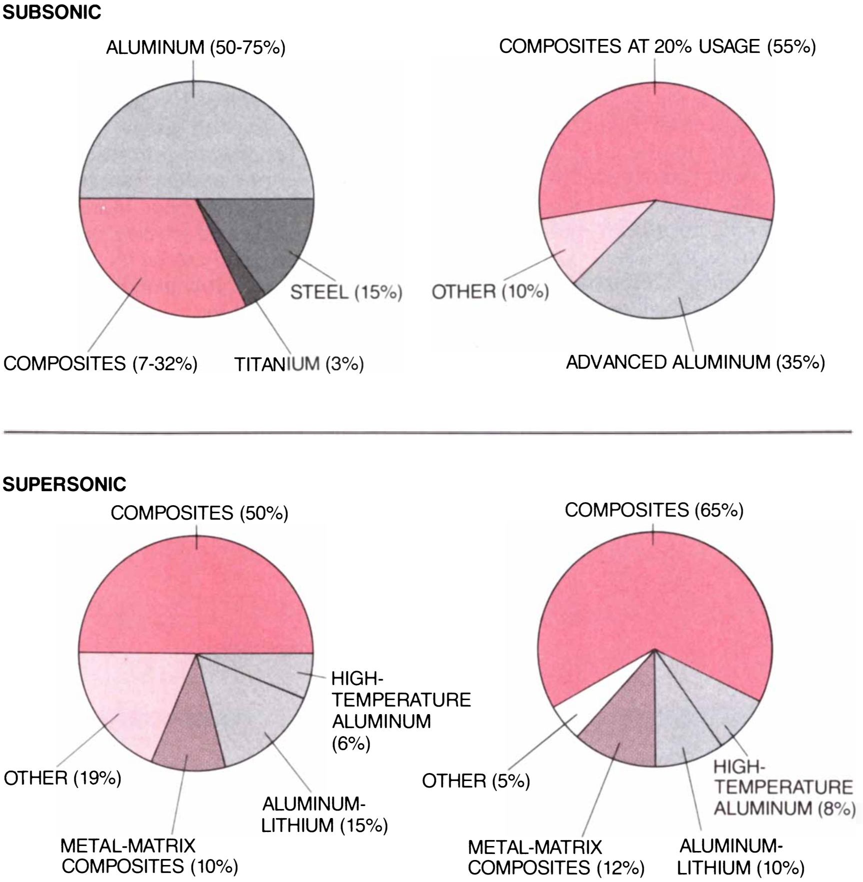
cope with such temperatures. Indeed, most of the primary structure of the airframe will be made of such materials in order to achieve good temperature resistance, light weight and a high ratio of strength to density. A sandwich structure consisting of two thin skins of titanium and a honeycomb titanium filler is a likely candidate.

In propulsion the new supersonic aircraft will need reductions in the weight of the engines and improvements in their performance. The compressors and combusters of the engines will have to run at higher temperatures than is now the case. They will therefore call for such materials as refractory metals, intermetallic compounds (titanium-aluminum and nickel-aluminum among them) and structural ceramics (silicon carbide, silicon nitride and carbon-carbon composites).

The transatmospheric airplane will require further quantum advances in the technologies of propulsion, aerodynamics, avionics (electronic control systems) and long-life materials for both low- and high-temperature applications. Propulsion technology is the biggest challenge, followed closely by materials technology for both the propulsion system and the airframe.

In all likelihood the craft will incorporate a dual propulsion system: ramjets for flight in the atmosphere and scramjets for space flight. A ramjet does away with the heavy air compressor needed in a turbojet; at supersonic speeds the air entering the engine compresses itself by ramming into a barrier. The compressed air is thereupon mixed with a hydrocarbon fuel for combustion. A scramjet (the word comes from supersonic combustion ramjet) works much the same way but burns hydrogen. The hydrogen is stored in the craft as an extremely cold liquid. The liquid hydrogen cools the engine. In the process it is warmed enough to become a gas, which serves as the fuel. Materials of interest are the nickel- and cobalt-based alloys, suitably coated, that resist high temperatures, and coated refractory alloys of niobium and molybdenum.

The airframe of the hypersonic transatmospheric craft will have to be made of strong, light, heat-resistant materials. A prospectus drawn up by Richard N. Hadcock of Grumman Aircraft Systems, Inc., envisions a fuselage made of heat-resistant metal alloys; wings and fins made of a carbon-carbon composite; engine inlets, ducts and nozzles made of ceramic-matrix composites; landing gear made of metal-matrix composites; internal parts made of organic-matrix composites, and fittings made of titanium.



ADVANCED MATERIALS will reduce weight in forthcoming subsonic and supersonic aircraft. The charts show the distribution of materials (*left*) and the weight saved (*right*).

The materials technology for the airframe builds on the application of a number of materials concepts that have already been put into practice in the space shuttle. For example, the new aerospace craft will have to withstand high external temperatures. Calculations have been made of the temperature at various places on the outer surface when the plane is in sustained flight at a speed of Mach 8 and an altitude of 88,000 feet. They range from 1,400 degrees F. along the top of the fuselage to 3,260 degrees at the nose.

The space shuttle's solution to similar conditions, carbon-carbon composite materials for the nose and leading-edge structures, can be applied to the transatmospheric craft. Such a material consists of a laminated structure made of layers of graphite-fiber cloth with a carbon matrix or binder and a silicon carbide coating. The fibers provide high strength and stability at high temperatures; the binder provides the same qualities plus rigidity and low porosity, and the coating provides resistance to oxidation. As a result the material is reusable because it is not ablated and continues to be effective in successive flights. (Engineers often refer to the material as RCC, for reusable carbon-carbon.) In addition the leading-edge structures of a transatmospheric craft will probably need an active cooling system. It would consist of pipes circulating a liquid-metal coolant.

The outside shell of the vehicle will probably be a three-part structure. From the exterior inward the components will be a layer of a heat-resistant metal alloy, a layer of insulating material and a strong but light layer made of an organic-composite material.

Another important component of the structure will be cryogenic tankage: an insulated storage system to maintain the liquid-hydrogen fuel at a low temperature. One can envision a tank consisting of a metal-matrix composite and a surrounding layer of insulation made of a foam material that is virtually impervious to the transfer of heat.

Satellites and missiles call for materials that are strong and stiff, low in density, resistant to heat and to expansion in a hot environment and good at conducting heat and electricity. Composite materials are now employed extensively in strategic missiles to save weight; every pound of inert weight saved in the upper stage increases the missile's range by nearly one nautical mile. With graphite composites rather than metals in the rocket motor, a missile gains almost 600 miles in range.

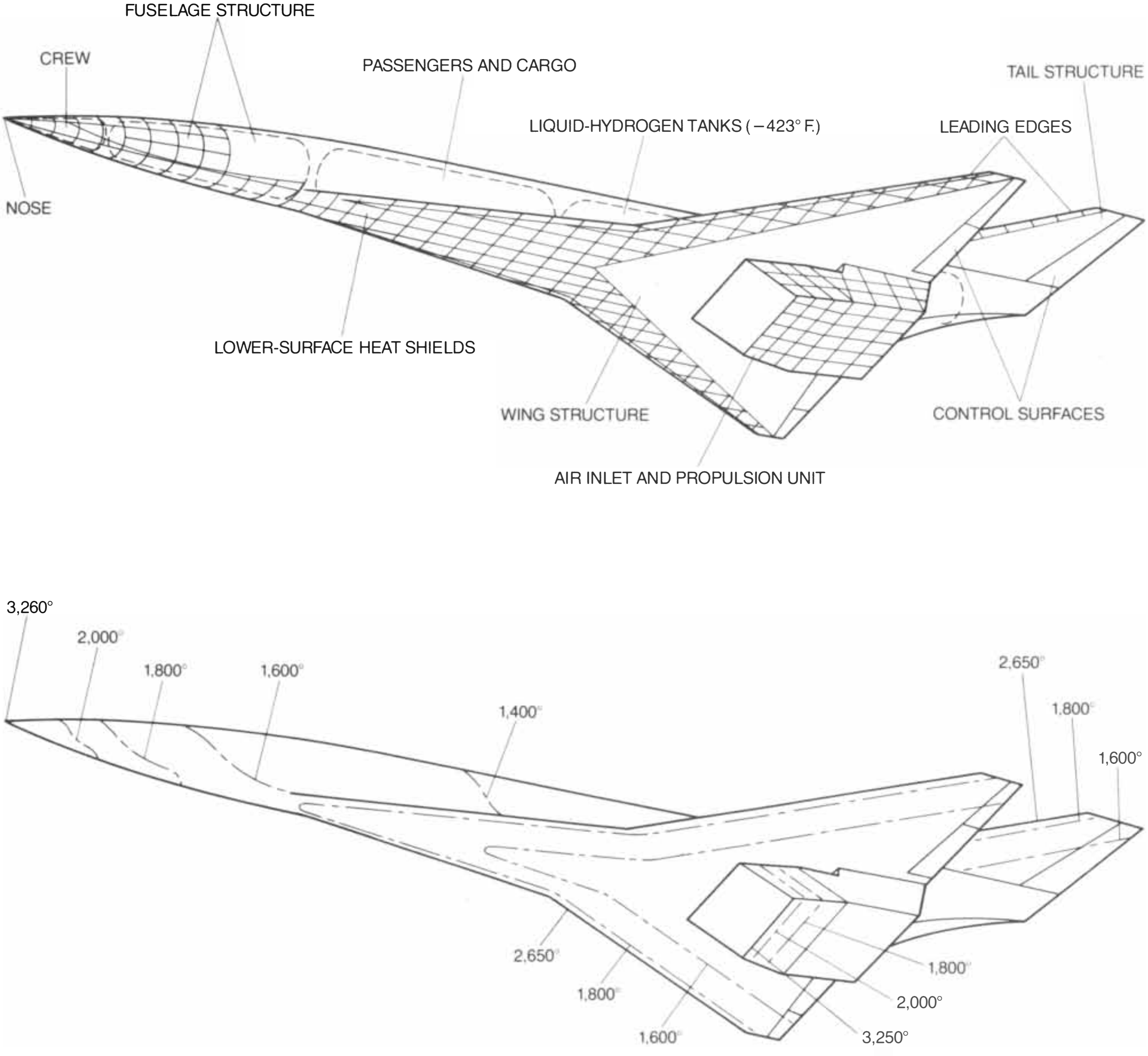
Spacecraft in the past have incorporated such structural materials as aluminum, stainless steel, titanium, magnesium, beryllium and Invar (an iron-nickel alloy noted for low thermal expansion). Today the tendency is toward incorporating materials that yield still better performance because they are high in stiffness, low in mass and stable in dimension. Metal-matrix composites are notable for those properties. Among them graphite-aluminum and graphite-magnesium show the greatest promise.

For the projected space station the National Aeronautics and Space Administration has proposed that the inhabited modules be made of aluminum. One reason is that composite materials can give off gases that might be toxic. Moreover, aluminum offers more protection against radiation. For other parts of the space station, such as large beams and trusses, composite materials are likely to be ideal because of their stiffness, low density and resistance to expansion.

The Strategic Defense Initiative is at such an early stage of planning that one cannot foretell what materials will serve it best. It seems certain, however, that the objectives being discussed will depend heavily on advanced structures and materials, some of them perhaps not yet discovered.

In the normal course of events the transition of a new material from the laboratory to the production line can take as long as 15 years. The properties of the material must be determined in detail and the best ways of fabricating it on a large scale must be ascertained. All of this work must be done with close attention to the final cost of the component in order to make sure that the finished aircraft is affordable.

The current challenges are to make advanced materials available at reasonable cost and to improve the processes of fabrication and assembly. If the challenges are met, the results will be more efficient production of civil and military aircraft and greatly improved aerospace vehicles.



TRANSATMOSPHERIC AIRCRAFT will pose challenges for developers of advanced materials because it will move at high speed in both the atmosphere and space. A configuration for the craft is shown at the top; estimates of the likely temperatures on the surface and in the propulsion system are at the bottom. The craft is expected to cross the Pacific in less than two hours.

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Launch on Warning?

Has the U.S. Government adopted a nuclear-defense policy that calls for "launch on warning"?

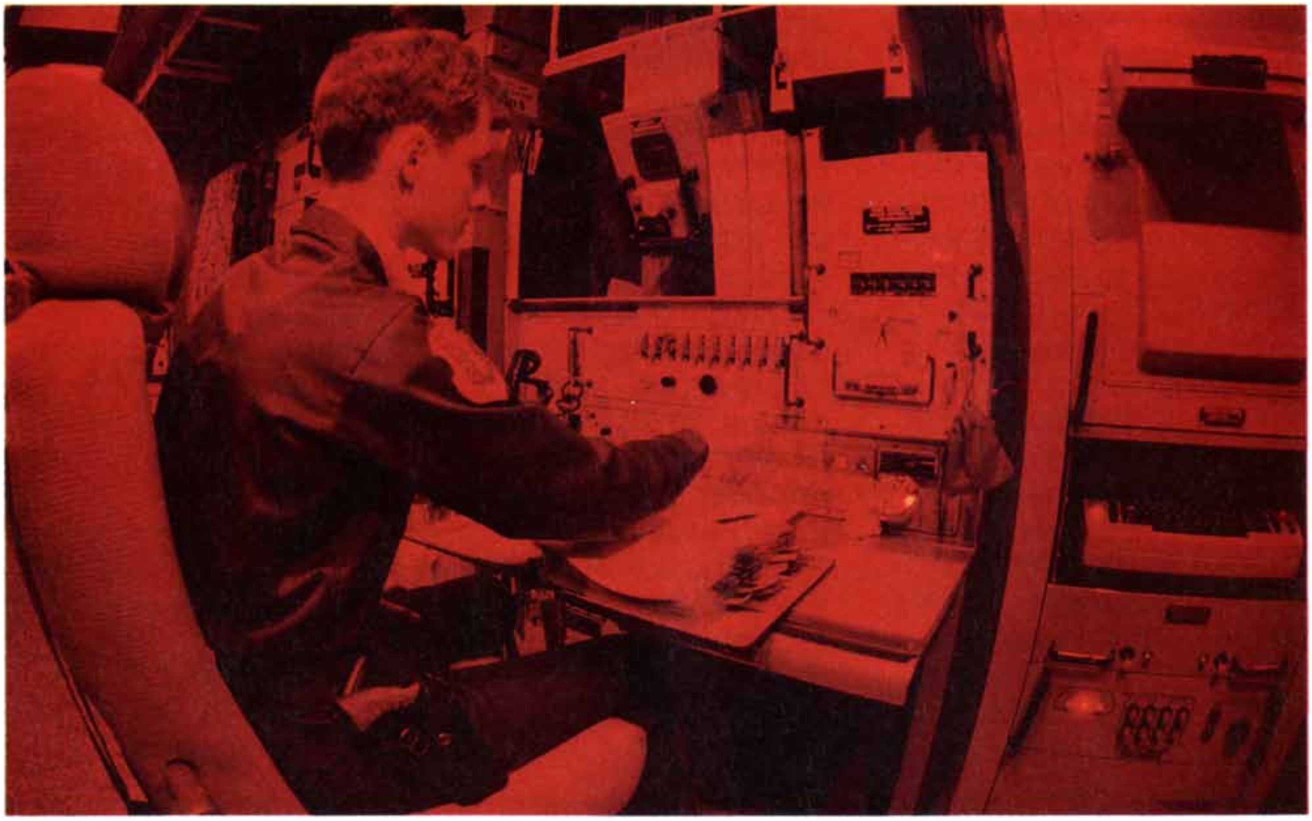
Since the 1960's, when Robert S. McNamara was Secretary of Defense, it has been explicit U.S. policy not to order a strategic nuclear strike, even if an enemy attack is detected, until the enemy's first nuclear punch has landed. Such a policy, its advocates argue, reduces the possibility that in a confrontation a misreading of electronic or other intelligence will lead to an erroneously launched retaliation. Yet there have recently been signs that McNamara's conservative stance has been abandoned for a "launch on warning" or "launch under attack" policy: strategic missiles would be lofted against targets in the Soviet Union as soon as reliable evidence is received that a Soviet nuclear-missile attack on the U.S. is under way.

Supporters of an early-launch policy justify it as a necessary response to improvements in Soviet weaponry that, they say, have left U.S. strategic-weapon systems—particularly the 1,000 or so intercontinental ballistic missiles (ICBM's)—vulnerable to a nuclear attack. Even more vulnerable to the Soviet weapon improvements may be the various systems for command, control, communication and intelligence (C^3I) on which military and civilian leaders would rely for the wartime disposition of all strategic forces. In the face of these putative vulnerabilities many defense analysts doubt that the U.S. forces would be able to mount a coordinated retaliatory strike after "riding out" a Soviet first strike. A relatively cheap and quick way to redress the situation would be through the implementation of a launch-under-attack policy. The argument is summarized in the catch phrase "Use 'em or lose 'em."

In any case, a launch-under-attack option, its advocates maintain, would keep the Soviets guessing about how the U.S. would respond to an attack, and keeping them guessing would presumably add to the effectiveness of the nuclear deterrent.

It is unclear how seriously the current Administration treats this option in formulating nuclear-war plans: public statements by Government officials are contradictory. Donald C. Latham, Assistant Secretary of Defense for Command, Control, Communications and Intelligence, seemed to dismiss the option outright when he stated before Congress this past spring that "our policy is not one of launch on warning, absolutely not." Yet the Administration's decision to field the newest and most powerful ICBM, the MX (or Peacekeeper), in what the Administration itself admits is a vulnerable basing mode could be interpreted as reflecting an increased reliance on an early-launch option as the principal means of guaranteeing the survival of silo-based ICBM's.

Testimony of other officials can be understood as confirming this interpretation. In hearings conducted by the Senate Armed Services Committee in February of 1985, General Charles A. Gabriel, Air Force Chief of Staff, was asked whether MX missiles in silos would not in fact be "sitting ducks" for Soviet military planners. Gabriel replied: "There are options that I won't go into. Obviously, if [the enemy] were going for our missile silos, there will be a period of time when we can see his weapons coming. We have sensors that tell us that. There are options that



MISSILE-LAUNCH CENTER is the final link in a command chain that begins with the president. Once the order to launch is given, such centers would execute it. The photograph, made by Jeff Lowenthal, was provided by Woodfin Camp and Associates.

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obviously do not make them sitting ducks."

In September of the same year General Robert T. Herres, commander in chief of the North American Aerospace Defense Command, spoke more generally to the House Committee on Government Operations: "We, in the military, would like to provide the National Command Authority with the flexibility to be able to ride out at least some portion of a nuclear attack if that should be necessary." Unfortunately, he added, it is not possible to achieve that goal without "a lot more survivability for some of your systems.... [We] have been able to keep up with the capability to launch on warning, but to go beyond that takes quite a bit of investment."

Bruce G. Blair, visiting scholar at the Brookings Institution, maintains that evidence for a launch-under-attack mode can be clearly discerned in the procedures that the president and his potential successors (the so-called National Command Authority) are meant to follow on receipt of a warning that an attack is under way. Blair prepared a classified report on the subject for the congressional Office of Technology Assessment. The Pentagon subsequently upgraded the classification, with the result that neither Congress nor the author himself now has access to it. Blair now says he "cannot reject the theory that the U.S. strategic forces are operationally geared to respond in the shortest amount of time." According to Blair, the nation's C^3I systems have in fact been structured for a de facto policy of launching under attack for the past 15 to 20 years.

McNamara concedes that a quick-response capability has always been favored in the design of strategic weapons, but he vehemently rejects the presumption that the U.S. ever had any intent to implement it in the guise of a launch-under-attack policy—at least during his seven-year tenure as Secretary of Defense from 1961 to 1968. McNamara emphasizes that the strategic forces of the U.S. are of such enormous size and capability that even if they were significantly degraded and therefore could mount only a haphazard retaliatory attack, they would still inflict devastating damage on the Soviet Union. This, McNamara argues, is the necessary and sufficient condition for deterrence. "What deters the Soviets is one thing: the knowledge that they cannot avoid suffering unacceptable damage even if they launch first and even if they target U.S. C^3I facilities," he says.

In spite of their different opinions, McNamara and Blair agree that such a launch-under-attack policy is seriously flawed. Such a response depends critically on an intricate network of space-based and ground-based warning sensors and data-processing equipment to detect and characterize the enemy missile attack. Yet the retaliatory attack order would have to be given within minutes after the initial Soviet attack has been detected. In such a stressful situation the specter of an accidental nuclear war triggered by technological malfunction or human mistake cannot be dismissed.

Blair also finds it unconscionable that the strategic forces, their C^3I systems and their launch-order procedures appear to have been configured in a way that would force the president into making the most critical decision he is ever likely to face—whether or not to engage the U.S. forces in a nuclear war—in the space of a few minutes. "Launch on warning precludes any chance for rationality, moral consideration or military reasoning—it is reflexive," he says.

A "no first use, no immediate second use" policy, McNamara and Blair maintain, would eliminate the temptation on the part of the Soviet Union to launch its missiles early in a crisis (before the U.S. does) and would reduce the likelihood that a malfunction or a misunderstanding could lead to nuclear war.

When McNamara was asked if he saw any value in keeping Soviet military planners in the dark about U.S. response options, he replied: "The last thing you want to do is to leave doubt in the mind of the Soviets over what you are going to do. I think it is a serious error to depend on launch on warning, and it is also an error to fail to state that we would not launch on warning."

Born Again

Nearly five years ago a Federal judge in Arkansas ruled unconstitutional that state's law requiring creationism and evolution to be presented on an equal footing in public school biology courses. Now the issue is back in the courts in the form of a challenge to a similar law adopted in 1981 by Louisiana. Within the next few months the U.S. Supreme Court will consider the question for the first time when it rules on the Louisiana statute. Louisiana has appealed two unfavorable rulings, one by a Federal district judge and one by a panel of the U.S. Court of Appeals. (The full appellate court voted eight to seven against rehearing the case.) In recent weeks the National Academy of Sciences, 17 state academies of science and 72 American winners of Nobel prizes have filed briefs urging the Supreme Court to find that the Louisiana law and others like it violate the First Amendment by requiring the teaching of a religious doctrine in public schools.

The Louisiana law is called the "Balanced Treatment for Creation-Science and Evolution-Science Act." It was enacted, its text states, "for the purposes of protecting academic freedom." The statute defines "creation-science" as "the scientific evidences for creation and inferences from those scientific evidences." It goes on to say that Louisiana's public schools will give the two subjects "balanced treatment" when the schools "deal in any way with the subject of the origin of man, life, the earth, or the universe." The statute decrees that "when creation or evolution is taught, each shall be taught as a theory, rather than as proven scientific fact."

This, contend the National Academy of Sciences and other filers of amicus curiae briefs, is religion in disguise. "Through books, lectures, pamphlets and other materials," the academy says in its brief, "creation-science organizations...argue that 'scientific' evidence and arguments support the conclusion that the universe, the world, living things, and man were created abruptly and fully formed from nothing through an instance or instances of 'special creation.'" Except when creationists are urging legislatures to mandate the teaching of "creation-science" in the public schools, the academy maintains, they "explicitly acknowledge that 'creation-science' is predicated on a belief in the literal, historical inerrancy of the Genesis account of creation."

The brief filed by the Nobel-prize group, the state academies of science and seven other scientific organizations focuses on the Louisiana law's attempt to distinguish between facts and theory. In science, the brief declares, the only facts are the properties of natural phenomena. By the continuous testing of hypotheses, scientists come to "accord a special dignity to those hypotheses that accumulate substantial observational or experimental support." It is such hypotheses that become known as scientific theories. By applying the "taught as a theory" requirement only to questions of origins, "the Louisiana legislature drew a scientifically untenable, pejorative distinction between evolutionary science and other scientific endeavors." To teach religious ideas mislabeled as science, the brief maintains, "is detrimen-

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tal to scientific education: It sets up a false conflict between science and religion, misleads our youth about the nature of scientific inquiry, and thereby compromises our ability to respond to the problems of an increasingly technological world."

MEDICINE

Arrested Motion

A drug many centuries old may now have found use in treating a disease of the central nervous system. The drug is colchicine, an anti-inflammatory agent extracted from a plant, the meadow saffron, and employed for more than 200 years as a treatment for gout. The disease is multiple sclerosis, in which the disruption of myelin (the fatty sheathing of nerve fibers) leads to the development of sclerotic, or scarlike, plaques in neural tissue. In the U.S. multiple sclerosis affects an estimated 250,000 people, or about one person in 2,000. Its symptoms include muscular weakness, visual deficits or spasticity, depending on the locations of the plaques. The tests were done by a group of investigators at Rockefeller University.

In choosing colchicine the investigators were reasoning from what is known about the drug. In general, colchicine binds to the intracellular protein called tubulin, preventing it from being assembled into microtubules, which in turn are among the structural elements of a cell's internal skeleton. The drug thus hampers the many cellular activities that depend on the cytoskeleton, including cellular movement. Specifically, colchicine limits the ability of the white blood cells called granulocytes to migrate to the uric acid precipitates that characterize gouty joints. Evidently the granulocytes worsen the condition.

In multiple sclerosis the investigators perceived a similar pattern: the motile cells called macrophages are known to invade the sclerotic plaques. It had long been assumed that the cells simply digest the debris of the disrupted myelin sheaths. Newer evidence suggested the macrophages might actively disrupt the myelin.

Twenty-five victims of multiple sclerosis took part in a clinical trial conducted by Herman J. Weinreb and his colleagues in John B. Zabriskie's laboratory at Rockefeller. The colchicine was given orally; it would normally not be able to pass from the bloodstream into the brain, but in multiple sclerosis the blood-brain barrier, consisting of tight seals between the endothelial cells that form the cerebral blood vessels, is breached at the sites of the pathology.

Five of the patients were early dropouts; of the remaining 20, 15 were stable or had improved when their condition was evaluated an average of 14 months into the trial. The adverse effects of the colchicine were chiefly gastrointestinal, notably diarrhea—the notorious side effect of the drug. (The activity of intestinal cells is highly dependent on their microtubular cytoskeleton.)

Meanwhile Michael J. Lyons and Roberto Amador, also at Rockefeller, had undertaken to test colchicine on animals. They exploited an analogue of multiple sclerosis called experimental allergic encephalomyelitis, or EAE, which is induced in experimental animals by injecting a brain-tissue emulsion, with the result that the immune system activates antibodies and primes them to attack the nervous system. The analogue was discovered, inadvertently, by Louis Pasteur and his colleagues. The rabies vaccine they developed in the 1880's contained molecules from the rabbit central nervous system, in which they had cultured the rabies virus.

Lyons and Amador injected brain-tissue emulsion into laboratory mice. Twenty-five mice in a group of 30 showed signs of EAE no later than 18 days after receiving the injection. A second group of 30 mice was given colchicine every other day for 18 days, beginning the day before the injection. None developed EAE.

The Rockefeller investigators hope to find in colchicine a treatment for multiple sclerosis that at least helps to arrest the progression of the disease. The toxicity and side effects of colchicine can be controlled by the careful regulation of dosage; alternative treatments that suppress the immune system appear to be much more toxic. The investigators are preparing a full-scale clinical trial.

Under the Skin

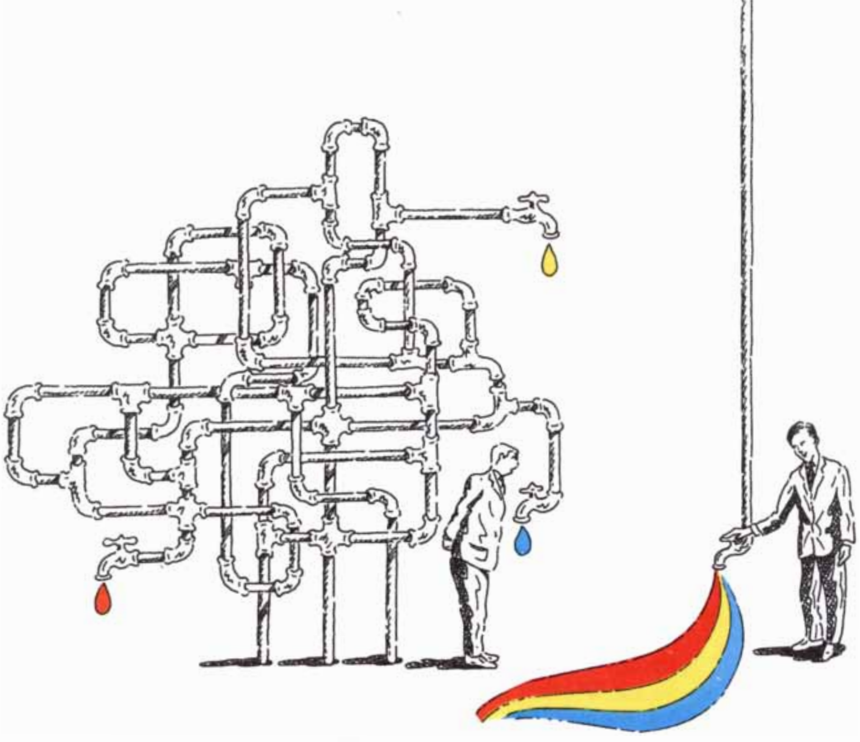
A birth-control method is more likely to be effective, other factors being equal, if it is convenient to use. Contraceptive implants are certainly convenient: the tiny capsules of silicone rubber are inserted under a woman's skin, where they gradually release their contents—a synthetic analogue of the female sex hormone progesterone—into the bloodstream. For more than a decade the Population Council, a private organization whose primary concern is promoting birth control in the Third World, has sponsored clinical trials of contraceptive implants. The most recent results are impressive and are likely to interest women in the developed countries as well. The investigators found that none of the 389 sexually active women in Colombia who carried implants for between one and two years became pregnant.

The results are reported in *Obstetrics & Gynecology* by Irving Sivin of the Population Council and his collaborators, three Colombian doctors who administered the implants at family-planning clinics in Bogotá and Ibagué. The implants consist of six capsules, each 34 millimeters long and 2.4 millimeters in diameter. The capsules are inserted, under a local anesthetic, through a single three-millimeter incision in the upper arm or the shoulder blade. Each capsule contains 36 milligrams of levonorgestrel, a progesteronelike chemical. According to Sivin, it is believed that the primary effect of the levonorgestrel is to render the cervical mucus impenetrable to sperm. (The standard contraceptive pill, in contrast, functions primarily by inhibiting the secretion of pituitary hormones that stimulate ovulation.)

The effect of the levonorgestrel is long-lasting because the chemical diffuses slowly through the silicone rubber. The Colombian results indicate that implants are equivalent to sterilization in the first couple of years after they are administered; earlier trials have found that the cumulative pregnancy rate after even five years is still less than 3 percent. What is more, whereas sterilization is generally permanent, the effects of a contraceptive implant can be reversed at any time by removing the capsules.

The major side effects of the implants are disturbances of the menstrual cycle, which affected nearly half of the Colombian women and eventually led 45 of the 389 to have the implants removed. Another 19 women dropped out of the study for other medical reasons, chiefly headaches. Still, the total dropout rate was no higher than it was among a control group of 104 women who depended on intrauterine devices (IUD's) for one year. Moreover, one IUD user got pregnant.

The main advantage contraceptive implants have over IUD's is that they carry no risk of pelvic infection; in the U.S., manufacturers faced with lawsuits have recently removed most IUD's from the market. The implants have been approved by health agencies in Ecuador, Indonesia, Thailand, Tunisia, Finland and Sweden, and clinical trials are now under way in the U.S. and China. Sivin said the Population Council plans to seek Food and



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Drug Administration approval of the implants within a year or so.

PHYSICS

Dark Matter Revisited

The universe contains far more matter than is apparent, according to both observation and theory. Where is the "dark matter" and what is it? Duane A. Dicus of the University of Texas at Austin and Vigdor L. Teplitz of the U.S. Arms Control and Disarmament Agency and the University of Maryland have suggested a novel answer to the venerable question.

Writing in *Physical Review D,* Dicus and Teplitz point out that there are really two astrophysical dark-matter problems: a small-scale one and a large-scale one. The small-scale problem concerns the motion of stars within galaxies and of galaxies within clusters of galaxies. Studies of such stellar motion indicate that galaxies and clusters may contain as much as 10 times more matter than is visible.

A particle called the neutrino heads the long list of particles that could embody the small-scale missing mass. Hypothetical particles have also been suggested, such as axions, which are required in certain grand unified theories. Another theory, known as supersymmetry, holds that every known particle has a partner with a different spin and a much greater mass; the photino, the "superpartner" of the photon, could also be a candidate for the dark matter. Still another possibility is strange matter, which consists of up, down and strange quarks bound in conglomerations of unlimited size. (Ordinary matter, in contrast, typically consists of quarks bound in threes; a proton, for instance, is made up of two up quarks and one down quark.)

The large-scale problem concerns the motion of the universe as a whole. In particular, the prevailing theory—known as the big-bang model—holds that the universe originated in a primordial explosion some 15 to 20 billion years ago and has been expanding ever since. What is the fate of the universe? Will it expand forever or will the expansion stop and will gravity draw the galaxies back together? The answer lies in the total density of matter in the universe. Currently that density is estimated to be about 20 times less than the critical density necessary to draw the galaxies back together. Yet recent models of the universe called inflationary theories require the density to be very near the critical density. To account for the discrepancy, astrophysicists have suggested that luminous galaxies could be outnumbered by regions of nonluminous matter. They have also proposed that decay products from heavy particles could supply the missing mass.

The work of Dicus and Teplitz stems from the last proposal, which was investigated in detail by Michael S. Turner of the University of Chicago. The two workers hypothesize that the resolution of both the small- and the large-scale problems could reside with the same particle species. Specifically, they show that if a particle species has a lifetime of several billion years, its massive particles, not yet decayed, could resolve the small-scale dark-matter problem, and its decay products could resolve the large-scale dark-matter problem. For example, a heavy muon neutrino or tau neutrino might decay into an electron neutrino. At least 17 different groups are now seeking to determine whether the various neutrinos have mass, and if they do, whether their values are sufficient to resolve the dark-matter problems. The candidates are not limited to neutrinos: axions and other exotic particles such as familons may, if they exist, decay into lighter particles too.

Topping It Off

Has the top, or *t,* quark been found? Its discovery would complete a list of particles generally thought to be the elementary constituents of matter. Although evidence for its discovery continues to accumulate, physicists are still reluctant to state that the elusive particle has been detected.

To search for the top quark, beams of high-energy particles traveling in opposite directions are made to collide with each other and the subsequent interactions are analyzed. Such interactions, numbering in the millions, have been recorded at the UA1 detector at CERN, the European laboratory for particle physics. Among them investigators have found 40 that could be the signature of the top quark. The results were reported by Ludwik Dobrzynski at the 14th annual SLAC Summer Institute of Particle Physics, held at the Stanford Linear Accelerator Center earlier this year. "We have the same data that first drew interest three years ago," Dobrzynski says, "but now we have five times as much of it."

The biggest problem in detecting the top quark is that its signature is indistinguishable from that of its close relative, the bottom, or *b,* quark. Physicists are therefore forced to calculate the number of bottom quarks they expect to see and then subtract that number from the total of the observed interactions in which bottom or top quarks are produced; the remaining events are thought to be attributable to the top quark. As particle accelerators with higher energies are built, top quarks should be produced more abundantly, making it clear whether the additional number of observed events is a statistical anomaly or actually corresponds to the production of a new particle.

If the evidence is confirmed, the top quark would be the sixth quark to be detected. Quarks were proposed in 1964 by Murray Gell-Mann and, independently, by George Zweig, both of the California Institute of Technology. The quark model was motivated by the desire to make sense of the array of particles—called hadrons—generated in high-energy collisions. Of the 100 or so hadrons known to exist, protons and neutrons are perhaps the most familiar. Originally, to account for the observed hadrons the quark model needed only three quarks (and their corresponding antiparticles, called antiquarks): the up, or *u,* the down, or *d,* and the strange, or *s,* quarks. A neutron, for instance, is made up of two down quarks and one up quark. The discovery of additional hadrons made it necessary to introduce the charm, or *c,* quark and the bottom quark. The six quarks, together with six leptons—the electron, the muon, the tau particle and three kinds of neutrino—and the antiparticles of each particle, bring the number of known elementary particles to 24. The large number of elementary particles suggests that a still deeper structure of matter may yet be found.

PALEONTOLOGY

Human Roots (and Branches)

Until recently the most widely accepted view of the prehuman family tree was that it includes two branches, which diverged from a common root about three million years ago. One lineage—the australopithecines—developed into a race of hardy, highly specialized vegetarians before becoming extinct. The second lineage culminated in human beings. This convenient scheme has been upset by the discovery in Kenya of a 2.5-million-year-old skull that does not fit any of the accepted categories. The ancient newcomer makes it clear that the hominid family tree has at least three branches, and additional rearrangements may be in prospect.

The prevailing view of hominid evolution, which is generally (although not universally) accepted, was first ad-


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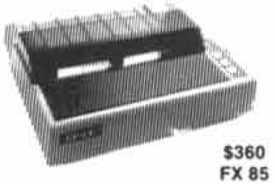

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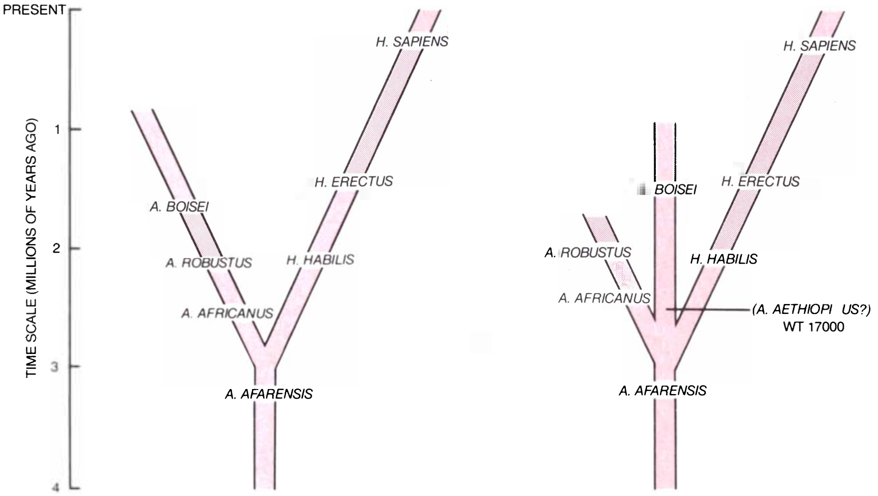
The oldest traces of *A. afarensis,* the common ancestor, date back 3.6 million years. Not long after three million years ago, Johanson and White's hypothesis goes, Lucy's descendants diverged genetically. One line ultimately emerged as *Homo habilis,* the first direct human ancestor. The other continued as australopithecines, passing through a form known as *A. africanus,* which gave rise in southern Africa to *A. robustus* and in eastern Africa to *A. boisei.* Both *robustus* and *boisei* are "robust" forms whose skull and facial muscles were highly evolved for chewing fruits and other vegetable matter. Indeed, one reason for the appeal of the Johanson-White hypothesis was the steady progress in the australopithecine line toward robustness.

The new find, made by Alan Walker of Johns Hopkins University, has spiked the wheel of that steady progression. Walker's skull, which is described in a recent *Nature* article, is in some respects the most robust ever found. Its large crests anchored huge temporalis muscles that provided tremendous power for chewing tough plant foods; its teeth are similarly specialized. Yet in other aspects the skull is quite primitive, and so it was perhaps not surprising that careful analysis of the surrounding geologic strata showed the skull to be 2.5 million years old: far older than any known *A. boisei* and just as old as *A. africanus.* Clearly the new skull (which is known by its museum accession number, KNM-WT 17000) cannot be a descendant of *A. africanus.*

What is it, then? Walker and his coauthors (Richard E. F. Leakey of the National Museums of Kenya, John M. Harris of the Natural History Museum of Los Angeles County and Francis H. Brown of the University of Utah) propose that WT 17000 is an early *A. boisei* that combines primitive and evolved traits. Others disagree. Johanson noted that the new skull shares about as many traits with *A. afarensis* as it does with *A. boisei* and is an excellent example of an intermediate form. Ultimately, he said, it will probably be considered a separate species descend-

KNM-WT 17000, a hominid skull found in Kenya, has upset accepted views of prehuman evolution. The skull, discovered by Alan Walker of Johns Hopkins University, is about 2.5 million years old. Some parts of WT 17000 are highly specialized for a vegetarian way of life, including the sagittal crest, which would have served to anchor huge jaw muscles for chewing plant foods. Other parts, among them the protruding face, are quite primitive. The photograph, made by Walker, is reproduced here with the permission of *Nature.*



MINIMUM REARRANGEMENT of the generally accepted human family tree (*left*) needed to accommodate WT 17000 is the addition of a third branch (*right*). The new branch extends from the primitive *Australopithecus afarensis* to the specialized vegetarian *A. boisei.* It parallels another vegetarian lineage and the prehuman *Homo* line. WT 17000 may define a new species called *A. aethiopicus.* The drawing is based on one in *Science.*

ed from *A. afarensis* and ancestral to *A. boisei*. If so, the minimum rearrangement of the family tree needed to accommodate the new species would be the addition of a new lineage leading from WT 17000 to *A. boisei* in parallel with the *A. africanus–A. robustus* line and the *Homo* lineage.

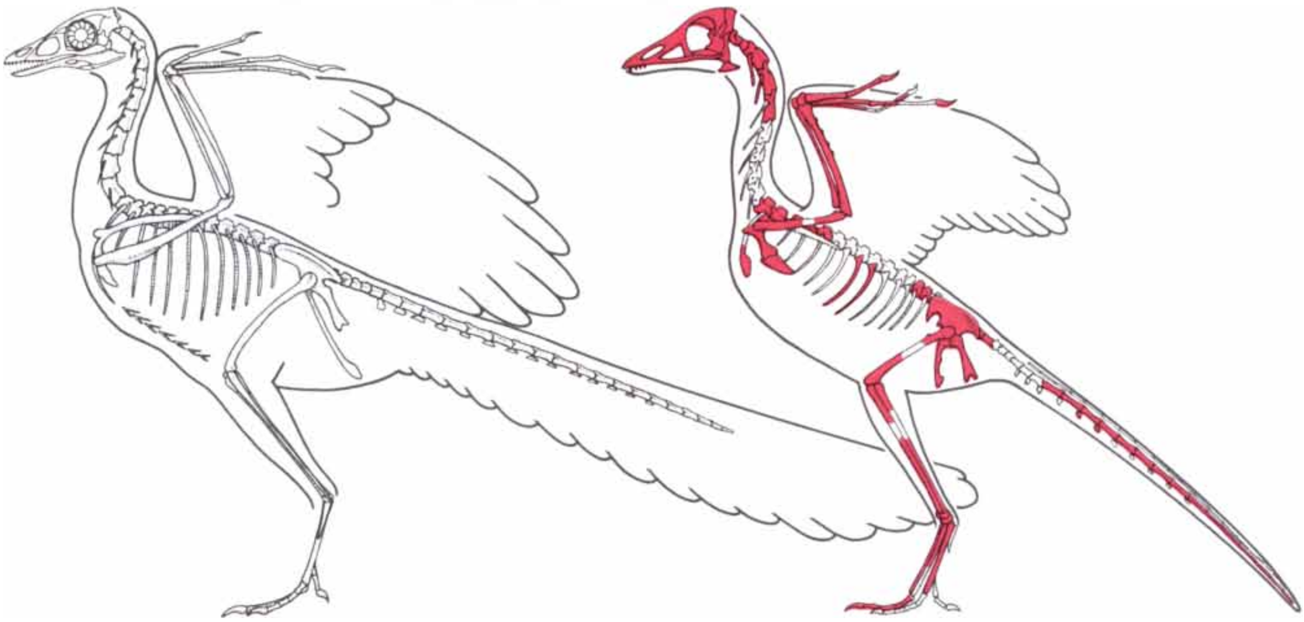
In solving one problem such a rearrangement could create other problems. The robust species were thought to constitute a single lineage largely because of the striking resemblance among them in their vegetarian adaptation. The proposed new tree implies that the same adaptation arose independently twice, which, if true, would be a remarkable degree of parallel evolution. Moreover, the key question of the origin of the *Homo* lineage remains unaddressed. A large gap in the fossil record has so far made it impossible to determine where the *Homo* line branched off from the australopithecines; the new skull does not appear to be near the branching point.

Indeed, to some observers WT 17000 (which is remarkably well preserved) has, by throwing accepted notions into disarray, chiefly served to clear the field for new hypotheses. Johanson seems to be more sanguine. "The new skull," he said, "does not knock out *afarensis* as the ancestor of *boisei*. It doesn't knock out *afarensis* as the ancestor of *Homo*. Most people, I think, still accept *afarensis* as the common ancestor of all three lines. What this specimen does—and I think it's a superb specimen to have—is to precipitate changes in the family tree. But that's what always happens in this field when you get new things you didn't expect to find."

Fossil Revisionism

Fossils may be set in stone, but their interpretation is not. A new find and a reinterpretation of old ones have challenged the standard view of two ancient creatures: the earliest bird and *Stegosaurus*.

First, the early bird. Two sets of



ANCESTRAL BIRDS are compared in these drawings. *Archeopteryx* (*left*) has been considered to be the dinosaurlike progenitor of the birds. Now two sets of fossil bones have been found in Texas, on the basis of which Sankar Chatterjee and his colleagues have reconstructed a much earlier, more birdlike creature, which they call *Protoavis* (*right*). Recovered bones are shown in color.

STEGOSAURUS has long been represented as having two rows of dermal plates along its back (*left*); paleontologists disagreed only on whether the plates alternated, as is shown here, or were paired. A new study done by Stephen Czerkas, on whose model the drawing at the right is based, shows that there was only a single row of plates. Drawings on this page were made by Patricia J. Wynne.

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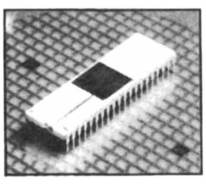

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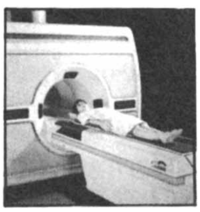

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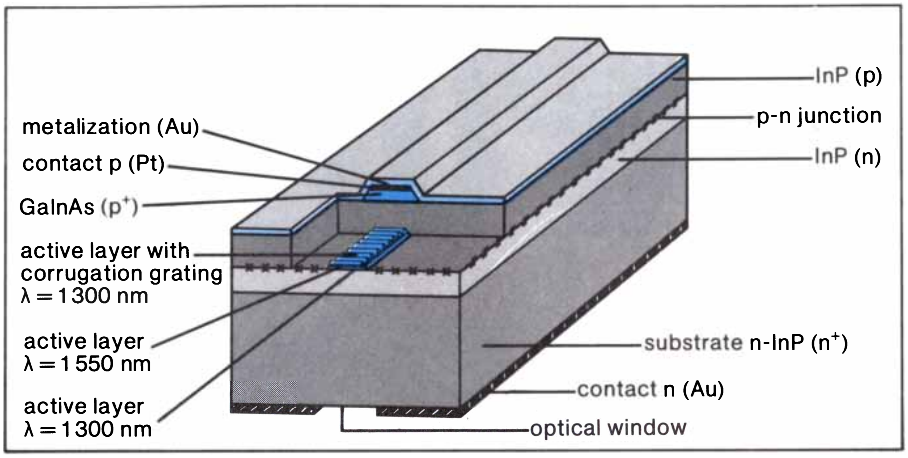

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THE MOCVD TECHNIQUE AND III.V MATERIALS.

In particular we have developed the metal organic chemical vapor deposition (MOCVD) method for growing phosphorus containing III.V materials such as indium phosphide. Indium phosphide is the basic material for Gunn diodes operating in the millimeter range up to 94 GHz and the starting material for 1.3 - 1.5 micrometer (μm) wavelength optoelectronic devices, the key components for high-bit-rate and long-haul links. MOCVD was first chosen because of its potential ability to process large areas of material and is therefore similar to the deposition techniques used in silicon production. MOCVD has since demonstrated that it can be used to grow sophisticated structures such as quantum well superlattices with an accuracy of one or two layers.

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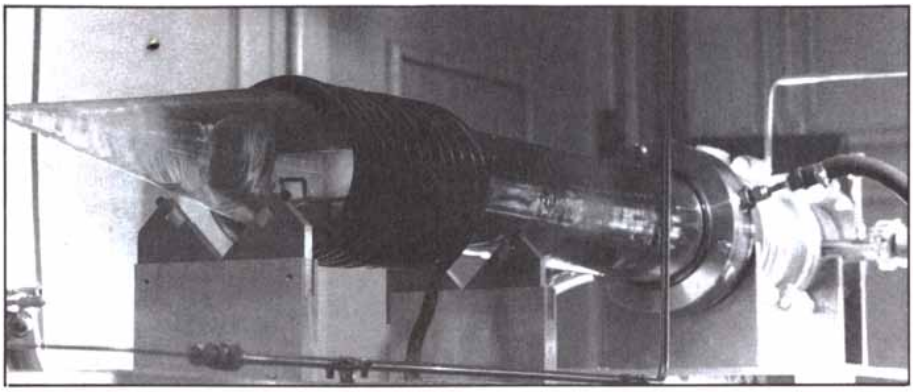

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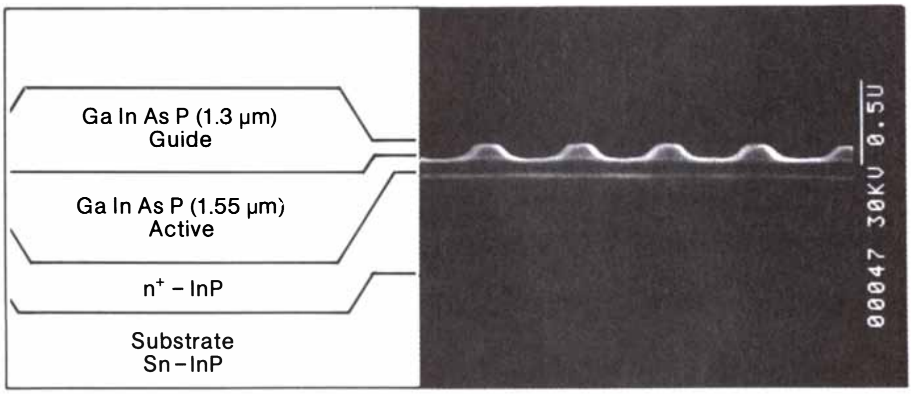

Electron microscope view of a cleaved edge showing the epitaxial structure after the regrowth on the corrugated surface.
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c) a quaternary confining layer λ= 1.3 µm } first epitaxy
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of the grating etched on the previous surface. } second epitaxy

The photograph shows that the regrowth took place without damaging the pattern.

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THE BRAINPOWER. THE WILLPOWER. THE WINPOWER.

POLARIS

bones found in western Texas have turned out to be those of crow-size birds that lived 75 million years before *Archaeopteryx,* which until now has been considered the earliest bird. The newly discovered creature, whose hind legs and tail resemble a reptile's and whose forward parts suggest a bird, is strong evidence for the theory that birds evolved from dinosaurs, according to Sankar Chatterjee of Texas Tech University, who led the discovery team. He calls the 225-million-year-old find *Protoavis,* or first bird.

This ancient creature had strong, heavy hind legs, a bony tail and a pelvis designed for running. These are all characteristics of dinosaurs, and at first Chatterjee thought he had found the remains of a juvenile meat-eating dinosaur. He changed his mind when he studied the other bones. *Protoavis* had a well-developed wishbone, a breastbone with a keel (which in birds serves to anchor flight muscles), hollow (and therefore lightweight) bones and long forelimbs.

The skull in particular suggests that *Protoavis* was a bridge between dinosaur and bird. The ears of the Texas fossils are well developed, an indication that the birds communicated by making sounds; most dinosaurs were mute. Moreover, dinosaurs, like modern crocodiles, had two holes in the temple behind the eyes to accommodate muscle bulges. In both *Protoavis* and modern birds these holes have merged with the eye socket (which is why birds' eyes are large in relation to body size). "This is clear-cut proof," says Chatterjee, "that *Protoavis* had crossed the dinosaur level and reached the bird stage."

The *Archaeopteryx* fossil found in Bavaria in 1861 is missing most of its skull, and it is not possible to tell from those remains whether *Archaeopteryx* had the hollow bones and keellike breastbone necessary for flight. In the jaws, however, Chatterjee sees evidence that *Archaeopteryx* was actually less advanced than the new find and probably represented a side branch of avian evolution. *Protoavis* did not have back teeth, whereas *Archaeopteryx* had a full set. The weight of teeth and strong jaws would make flying less efficient.

Paleontologists who are not sure *Protoavis* was a bird point out that the new fossils have no feathers; the *Archaeopteryx* fossil did include feather impressions. Chatterjee responds that feather impressions are often not preserved, and that some bones of the Texas fossils do show small nodes to which feathers were likely to have been attached. He thinks *Protoavis* could certainly have fluttered away from predators.

Protoavis makes evolutionary sense of the proliferation and diversity of bird species that began about 100 million years ago. The similarity of some of these birds to modern families has long suggested they shared some ancestor older than *Archaeopteryx*.

As for *Stegosaurus*, its profile is familiar to anyone who cares about dinosaurs. It is the one with the double row of plates sticking up out of its back. Or is it? Stephen Czerkas, a freelance paleontologist, has reexamined all the available fossil evidence. At a symposium at the Natural History Museum of Los Angeles County he maintained that *Stegosaurus* actually had only a single row of plates.

The double-row assumption had suggested that *Stegosaurus* was warm-blooded and cooled itself by channeling air between the two rows of plates. Instead, Czerkas says, the dinosaur (like a modern cold-blooded reptile) depended on exposure to the sun to regulate its body temperature. Its cold blood would have been warmed as it coursed through a single row of flat, upright plates—"the best solar panels any dinosaur ever had."

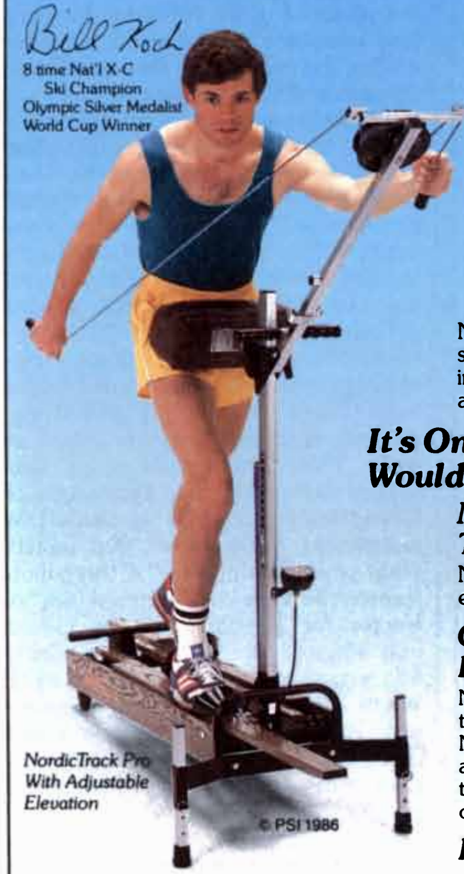
Czerkas believes the wide bases of the plates in the dinosaur's neck and shoulder regions held the plates tilted outward from the midline in an alternating pattern. If a stegosaur died on its side, the upper parts of these dermal plates would overlap even though the bases of the plates were in a single line. (The remaining plates, along the back and the tail, pointed straight up from the midline.) It was the overlapping of the shoulder and neck plates of a *Stegosaurus* fossil discovered in Colorado in 1886 that first led paleontologists to think the dinosaur must have had two rows of plates.

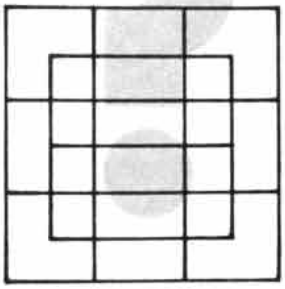
TECHNOLOGY

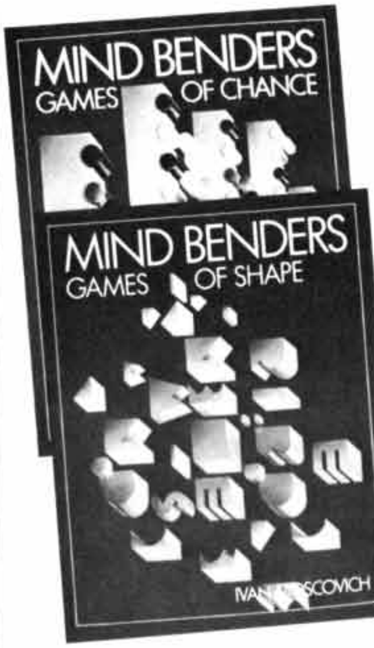
Engineered Tolerance

Ever since molecular biologists discovered how to transfer foreign genes into plants it has been clear that the technique might serve to make a crop plant resistant to a herbicide. It would then be possible to apply a weed killer to a growing crop without destroying the crop along with the weeds. A first step toward achieving such engineered herbicide resistance has now been taken.

The potent herbicide called glyphosate kills plants by binding to and inactivating a plant enzyme, EPSP synthase, that catalyzes the synthesis of a num-







ber of proteins. Normal plant cells have a single copy of the gene encoding EPSP synthase. Dilip M. Shah and a team of colleagues at the Monsanto Company cultured a line of petunia cells (*Petunia hybrida*) in increasing amounts of glyphosate. The cells came to tolerate the herbicide. The molecular basis of the tolerance turned out to be overproduction of EPSP synthase: in the presence of the herbicide the cells had somehow amplified the gene encoding the enzyme, so that there were 20 copies of the gene per cell.

The Monsanto workers report in *Science* that they proceeded to isolate and clone the EPSP synthase gene. Then they set about applying recombinant-DNA techniques to make it an automatic self-amplifier. They did so by attaching to the gene a "promoter" region taken from the DNA of the cauliflower-mosaic virus. The promoter helps the virus to replicate rapidly when it infects a plant, and it had been shown to cause high-level production of foreign genes in plants as well. The recombinant gene was spliced into a plasmid (a small circle of DNA) that is carried by *Agrobacterium tumefaciens,* a bacterium that infects plant cells. The plasmid is thereupon transferred to an infected plant [see "A Vector for Introducing New Genes into Plants," by Mary-Dell Chilton; SCIENTIFIC AMERICAN, June, 1983]. When bacteria carrying the recombinant plasmid were allowed to infect normal petunia cells, the engineered EPSP synthase gene was transferred into the plant cells.

In the resulting "transformed" petunia cells a single copy of the gene was found to do the job of multiple copies: it produced more EPSP synthase than even a heavy dose of glyphosate could inactivate. The transformed cells formed lumpy calluses, which grew in the presence of glyphosate. Plants grown from the calluses flourished even when they were sprayed with from two to four times the dose of a commercial glyphosate herbicide that killed 100 percent of a control group of untreated petunia plants.

Record High

In their quest to achieve a magnetically confined, self-sustaining fusion reaction, scientists and engineers at the U.S. Department of Energy's Princeton Plasma Physics Laboratory have attained the highest temperature ever recorded in a laboratory: 200 million degrees Celsius. The temperature was reached in the laboratory's Tokamak Fusion Test Reactor (TFTR). The achievement is seen as a significant step toward the development of fusion reactors that generate electricity.

Fusion is achieved by heating a gas composed of the hydrogen isotopes deuterium or tritium to exceedingly high temperatures. Such an ultrahot gas, called a plasma, consists of individual electrons and nuclei. When two of the nuclei collide, they can form a helium nucleus and release energy in the process. Yet the attainment of high-temperature plasmas is not sufficient for practical power generation. It is also necessary to keep enough nuclei around long enough for the reaction to sustain itself, and so the plasma is confined in magnetic fields. The efficiency of a fusion reactor's magnetic confinement is measured by the so-called Lawson parameter: the product of the particle density and the mean energy-confinement time.

In the TFTR, deuterium gas in a doughnut-shaped chamber is heated, by subjecting it to a fluctuating magnetic field whose lines run through the hole in the doughnut, until it becomes a plasma. Such a field generates a current in the gas, and it is this current that heats the gas (much as current flowing in a wire heats the wire). The plasma is confined by two other sets of magnets. To reach the record temperature additional heating was necessary. This was done by bombarding the plasma with a powerful beam of accelerated deuterium atoms.

The goal of the TFTR experiments is to produce a plasma that generates an amount of fusion energy equal to the amount of energy required to heat and confine the plasma, a condition that is known as the break-even point. To reach the break-even point at a temperature of 200 million degrees a Lawson-parameter value of about 5×10^{13} particle-seconds per cubic centimeter is required. Unfortunately, when the Princeton group reached the 200-million-degree mark, the Lawson parameter was only about a fifth of what is required for break-even.

In earlier TFTR experiments, which were performed without the additional particle-beam heating, high-velocity pellets of frozen deuterium had been injected into the reactor; as the pellets evaporated they deposited deuterium ions in the plasma. In these experiments the Princeton workers found they could reach Lawson-parameter values of 1.5×10^{14} particle-seconds per cubic centimeter, but at a temperature of only 15 million degrees. At such Lawson-parameter values, temperatures six times higher than that would have been necessary to reach the break-even point.

The investigators are confident that

by combining the pellet-injection technique with the particle-beam heating, and by switching from deuterium fuel to a mixture of deuterium and tritium, the break-even temperature and Lawson parameter can be reached simultaneously. Of particular interest to the investigators, however, is evidence collected during the experimental runs that appears to indicate the existence of a so-called bootstrap current. The bootstrap current was predicted to arise from a general outward drift of plasma particles. Such a motion produces a current that in turn generates a magnetic field. The current could theoretically be exploited to make the plasma confine itself, and this might allow the fusion reaction to proceed at a steady power level rather than in the cyclic manner in which the TFTR now operates.

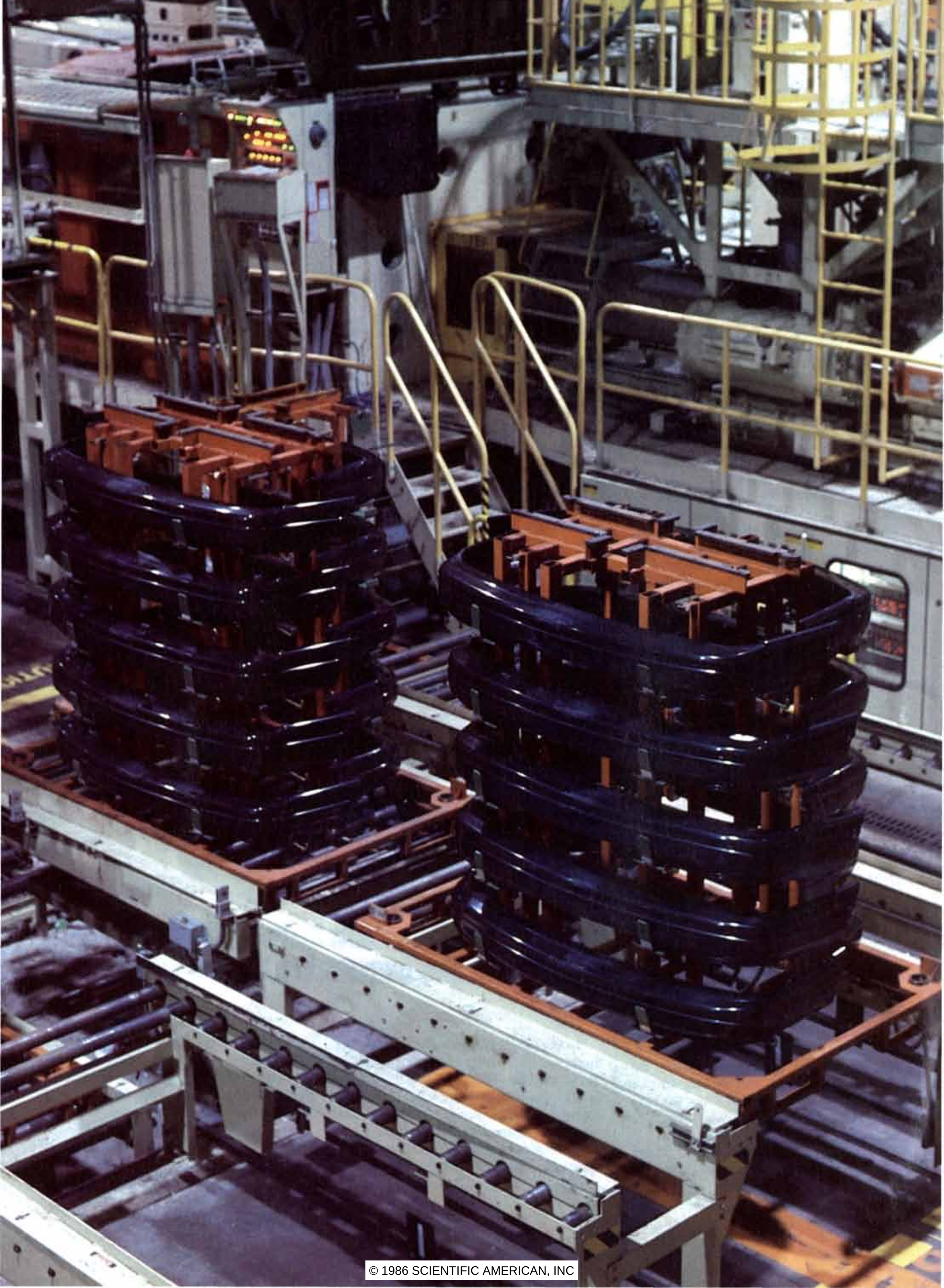
Heavy Breathing

Computer chips, certain pharmaceuticals and a number of other products have to be manufactured in a "clean room" made as free as possible of dust and other contaminants. Manufacturers often go to great lengths to achieve this end, requiring workers to wear "bunny suits," face masks and gloves and installing elaborate systems to filter the air. Now they must deal with an unsuspected hazard: particulate matter exhaled by a smoker for as much as an hour after smoking. Stuart A. Hoenig of the University of Arizona did a set of experiments that confirmed the phenomenon.

In one experiment a smoker and a nonsmoker breathed into particle counters set up 25 millimeters from their mouths. In the first minute after the smoker had finished a cigarette his breath contained 30,000 particles per cubic foot and the nonsmoker gave off 1,000. After 10 minutes the smoker was down to about 6,000 particles. Most of the particles turned out to be epithelial (surface) cells from the mouth. The particle sizes ranged from .2 micrometer to 12 micrometers.

In another experiment the participants drank coffee between tests. Apparently the smokers swallowed many of the epithelial cells with the coffee. That brought down the smokers' particulate emissions, but even after 63 minutes there was a significant difference between a pack-a-day smoker and a nonsmoker. Even when the nonsmoker ate 12 crackers, his particulate emission did not increase.

What to do? Hoenig found a simple solution: Get the smoker to take a drink of water before returning to the clean room.



Materials for Ground Transportation

The 40 million cars and trucks produced every year consume a huge quantity of material. Far more of it is now aluminum, plastic or high-strength steel; correspondingly less is ordinary steel or cast iron

by W. Dale Compton and Norman A. Gjostein

One of the principal determinants of the modern style of life is the capacity for moving people and goods quickly from one place to another. The freedom to move to another city, to live far from where one works and even to travel long distances for shopping, dining or recreation depends on fast and reliable means of ground transportation. While some of this movement is provided by buses, subways or trains, most of it is accomplished by that most private of conveyances: the automobile. Each U.S. household owns an average of 1.5 cars and trucks; a total of more than 164 million registered vehicles cover nearly two trillion miles a year. More than one-sixth of the gross national product is consumed by the cost of moving goods and people on the ground.

Nor is the rest of the world far behind the U.S. In the world as a whole there is now one vehicle for every 10 people, a ratio roughly equal to the one that prevailed in the U.S. in 1920. As the pace of industrialization increases in the rest of the world, that ratio will undoubtedly rise. The increasing demand for automobiles will be met by an industry that is now quite international. Of the 42 million cars and trucks manufactured in 1984, more than 15 million were exported. By far the largest share of the total production was accounted for by the U.S. and Japan, each of which built about a fourth of the 42 million vehicles that came off assembly lines in 1984.

Such a large volume of production entails enormous quantities of materials. Every year some 56 million tons of iron, steel, aluminum, plastic and other materials are used up in the manufacture of cars and trucks. The relative importance of each material is determined by many factors, some of which have changed markedly in recent years. As a result the average vehicle now contains far more micro-alloyed high-strength steel, cast aluminum and fiber-reinforced plastic than it did a decade ago. The trend shows no sign of abating. Indeed, 10 years hence many cars may be made mostly of plastics. Engines and transmissions could contain significant quantities of magnesium, ceramics and new composite materials. Along with the changes in materials content have come dramatic shifts in the way vehicles are designed and built.

The forces responsible for reshaping the automobile industry first became apparent in the late 1960's. During the 1950's trade barriers had been quite common, and as a result exports were not of major significance for any of the world producers. That situation began to change with the establishment of the European Economic Community, which lowered trade barriers in western Europe. Soon thereafter the cost of shipping finished vehicles began to decrease. By the late 1960's Japan had developed an aggressive export-oriented automobile industry. Then in the early 1970's the first energy-price shock was felt. Rising energy prices and lower trade barriers combined to bring into being a world market in which the producer with the lowest costs holds a commanding economic advantage.

Nowhere were these changes felt more strongly than in the U.S., where the effect of higher fuel costs and competition from Japanese, German and other foreign manufacturers was aggravated by new Federal regulations aimed at increasing safety, reducing emissions and improving fuel economy. Meeting the new guidelines required major changes in the automotive product. By "downsizing" the vehicle and substituting lightweight materials, the weight of the average car was sharply reduced. Consequently the fuel economy of domestic products rose dramatically—from an average of 13 miles per gallon in 1974 to 25 in 1985. Improved crash protection was achieved by new design concepts and increased use of high-strength steels. Emissions were reduced by including a catalytic chemical reactor in the exhaust system of the vehicle and by redesigning the engine and transmission.

In their effort to meet Federal standards and match the Japanese and German imports in fuel economy and quality, U.S. manufacturers faced a major economic challenge. Companies operating in Pacific Rim countries such as Japan and South Korea have much lower costs than their U.S. competitors. The disparity is due partly to lower labor costs in the Pacific Rim countries and partly to government policies there that influence the cost of capital and the return on investments. U.S. industry's response has been broad and deep. In addition to drastic cost cutting there is now under way a fundamental reexamination of the process by which vehicles are designed, developed and manufactured; the objective of this process is not only to reduce costs but also to improve the quality and reliability of the product.

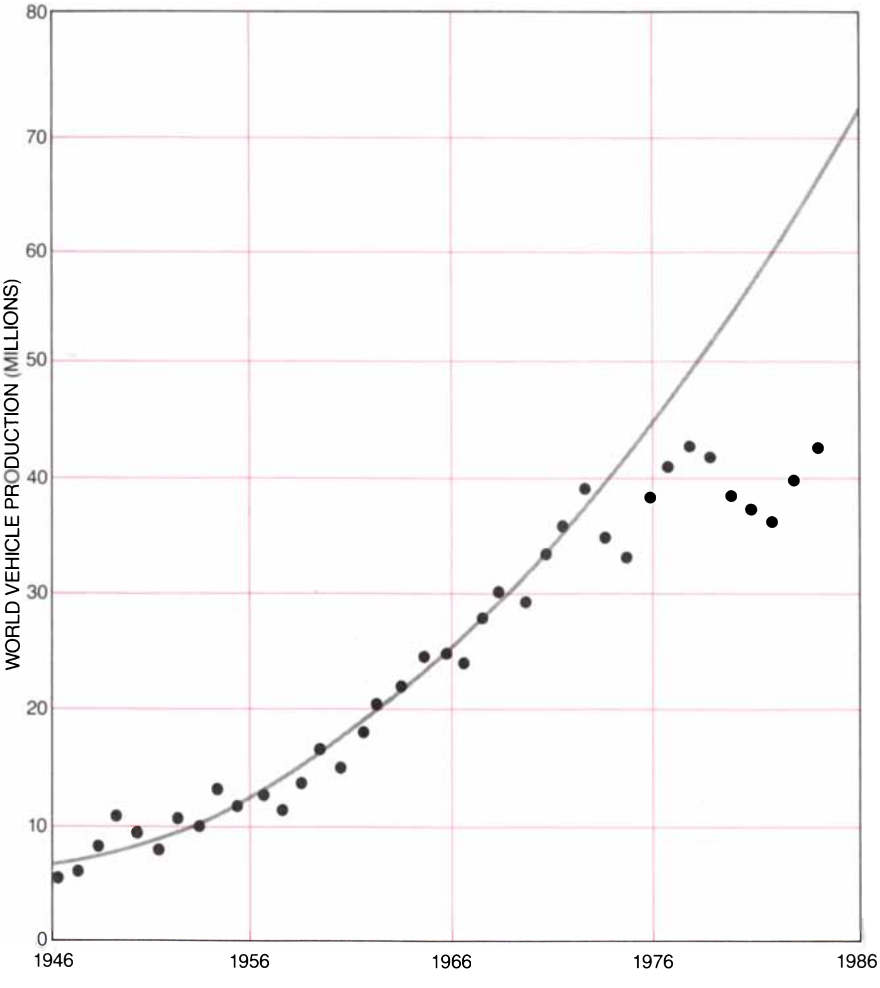
PLASTIC BUMPERS for the Ford Taurus are manufactured in a highly automated plant at Milan, Mich., near Detroit. The Taurus is a small sedan whose bumpers are molded from Xenoy (a new high-strength polymer blend made by the General Electric Company). Newly formed bumper parts are shown being conveyed from the automated injection-molding equipment in which they are made. Plastic is one of the lightweight materials—others are aluminum and high-strength steel—that are being employed in increasing quantities in the manufacture of cars and trucks. As the fraction of the average vehicle made of such materials was rising, the fraction made of ordinary steel or cast iron fell.

The design of a car or truck is a hierarchical process that begins with the formulation of a business strategy and an overall product plan. The first step is to specify the type of vehicle, such as passenger car, sports car or small pickup truck. The next phase is the selection of general specifications such as size, weight, performance levels, features (the inclusion of a hatchback, for example, or four-wheel drive) and aerodynamic characteristics. Cost and quality targets are set for each vehicle. Depending on the business strategy chosen, the vehicle may be constructed entirely from new parts or from a combination of new parts and those already in production. In both cases the starting point for the design of the vehicle is a large fund of accumulated knowledge.

When the general specifications for the vehicle have been chosen, the designer must work out the specifications for individual components. At first the designer's main concerns are functional performance and what are referred to in the industry as geometry, package, cost and weight: each part must fit in the space allotted to it, must match the surrounding parts and must be of a design that can be built within the cost and weight guidelines that have been established for each subsystem of the vehicle.

The design of components is perhaps the aspect of automobile design on which computers have had the greatest effect. At most major automobile manufacturers a designer can now use computer programs that simulate the performance of a vehicle. The programs are based on a library of computer models of vehicle components. The designer selects parts from the library and "assembles" them into a hypothetical vehicle by means of the computer's modeling capabilities. Such computer simulations provide a preliminary test of the vehicle's capacity to meet the objectives that have been set for fuel economy, exhaust emissions and weight.

Geometry, package and functional performance are significant criteria in component design. Another factor—the choice of a fabrication process—is critical, because it strongly influences the final cost and quality of a component. Until recently, automotive design was a serial process and fabrication was considered at a late stage, after geometry and package and then functional performance. The serial design process was a long one, partly because tests of functional performance generally called for constructing prototype components and vehicles; the time required for the construction and testing of successive prototypes lengthens the design cycle. It has not been unusual for five or six years to elapse between the first design specifications and the production of the first commercial vehicle from the design.



WORLD VEHICLE PRODUCTION has leveled off after rising since World War II. The solid line indicates the trend from 1946 through the early 1970's. Had the trend continued unabated, production would be 70 million cars and trucks per year; in actuality it is 42 million. About 56 million tons of materials is needed to construct those vehicles.

The computer will undoubtedly assist in reducing the time required to complete a design and bring it into production. The key to such reductions is the transformation of design from a serial process to a simultaneous one, a transformation that is already well under way. In simultaneous design the first step is to use the computer to define the geometry of the part and evaluate its package space. The geometric data are made accessible to engineers so that several types of analysis can be carried out at once. For example, the functional performance of vehicle components can be simulated by computer while the detailed properties of the materials employed in making the components are being considered. Fewer prototypes are required and the design cycle is reduced.

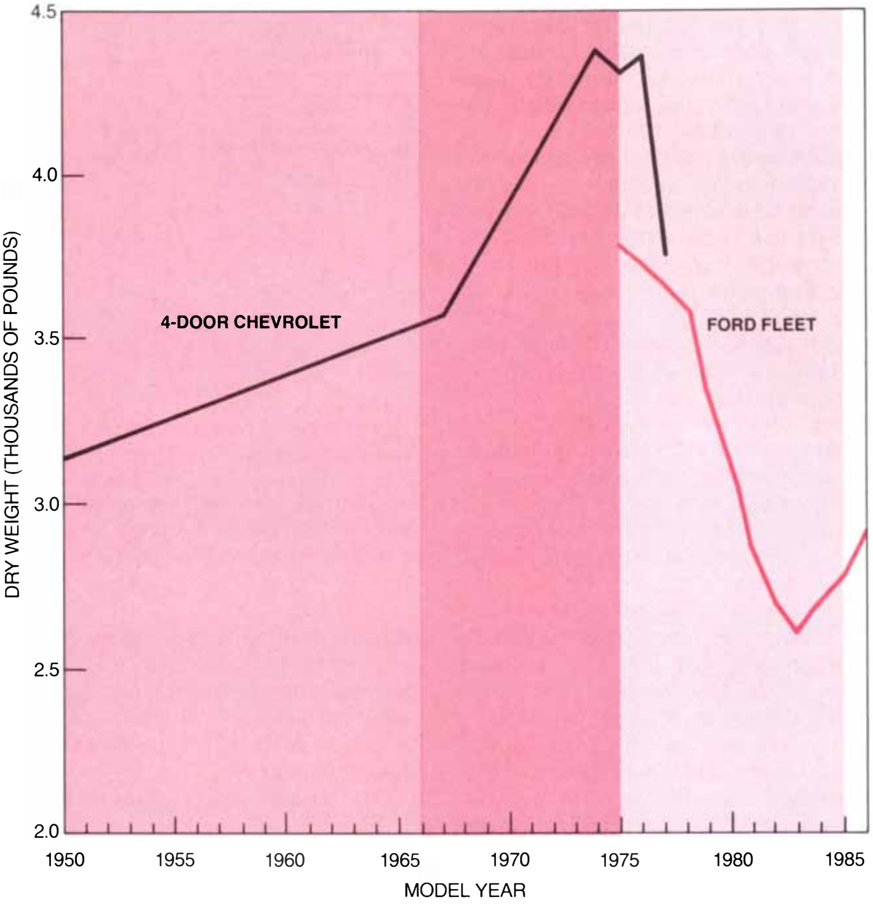
Furthermore, simultaneous design methods make it possible to consider the manufacturing alternatives much earlier in the design process. After the part has been shaped using a computer-aided design program, the geometric information stored in electronic form can be employed to evaluate the processes by which the part could be fabricated. The geometric data can also be manipulated to generate engineering drawings or to examine in detail the feasibility of aspects of the manufacturing process such as the cutting-tool paths that will later be programmed into the microprocessors of machine tools.

Significant as the fabrication process is, it cannot be considered alone but must be examined in relation to a particular material. Indeed, frequently several alternative processes must be considered in relation to particular materials. There are generally only a few tenable combinations of process and material for each component, because of the limitations imposed by the function of a part, its shape and its connections with other parts in the finished vehicle. If the part is an engine block, for example, probable combinations include casting aluminum and casting iron. For bodies there are several combinations (stamping steel sheets, molding plastic panels and stamping aluminum sheets); for crankshafts there are generally two (casting iron and forging steel).

Having narrowed the field to the few workable options, how does the designer choose one of them? Cost and quality are key considerations. In weighing cost the mutual influence of material and process is particularly clear, because both contribute to the total cost of manufacturing. The cost of the material incorporated in a component can be estimated by a fairly straightforward computation. Finding the cost of fabrication entails a more complex calculation that includes all the fabricating steps. When a gear, say, is being designed, forging, machining, heat-treating, surface hardening and annealing must all be brought into the calculation. The reason for weighing the cost of processing at the same time as the cost of materials is that a more expensive material may be less expensive to fabricate, offsetting or perhaps even reversing the advantage of the cheaper substance.

Because of increases in the price of fuel, competition from efficient Japanese and European imports and the need to meet Federal fuel-economy standards, the process of materials selection has in recent years been strongly influenced by the need to reduce weight. Consequently a host of lightweight materials have begun to replace conventional materials in U.S. cars and trucks. Among them are high-strength steels that contain minute amounts of elements such as titanium or vanadium. Micro-alloyed steels can have strength ratings of 50, 60 or even 80 thousand pounds per square inch (p.s.i.) compared with the 30,000 p.s.i. that is typical of mild (conventional) steels. Although micro-alloyed steels were developed in the 1960's, production on a large scale did not begin until the mid-1970's, when U.S. automobile manufacturers' desire for savings in weight created a strong demand for lighter and stronger metals.

Other lightweight materials—particularly aluminum and plastics—are also making a contribution to weight reduction. Before substituting any of these lightweight materials for conventional ones an engineer must determine just how much weight is likely to be saved by the substitution. The saving cannot be determined merely by comparing the density of the lightweight material and that of the conventional one it replaces. A part's function and the engineering qualities of the materials must also be taken into account, and when they are, the saving in weight is often seen to be much less than it would appear to be on the basis of density alone.



THREE PERIODS can be distinguished in the history of U.S. cars and trucks since World War II. The graph shows what happened to the weight of passenger cars in each of them. The black curve is for the average four-door Chevrolet; the colored curve is for the sales-weighted average of the Ford U.S. passenger-car fleet. During the postwar period demand for "extras" such as power steering led to a rise in vehicle weight but to little change in materials content (*medium color*). From the mid-1960's through the mid-1970's new Federal rules governing safety and pollution led to further increases in weight; some innovative materials were introduced (*dark color*). Since then foreign competition and higher fuel prices have led U.S. manufacturers to reduce vehicle weight by "downsizing" and by substituting lightweight materials for conventional ones (*light color*). Recently fuel costs have declined and the weight of the average Ford has started to rise again.

Comparing cast aluminum with a more conventional material, cast iron, shows how engineering properties help to determine how much weight is saved. One might think the substitution of cast aluminum for cast iron would always lead to a considerable reduction in weight, because cast aluminum is much less dense than cast iron: a cubic foot of the lighter material weighs 63 percent less than an equal volume of the heavier one. For many engineering applications, however, the actual saving is much less, since a greater volume of aluminum must be used to compensate for the superior properties of the cast iron. For instance, in a hypothetical application where the only design constraint on the components is that equal stiffness is required of them, the weight saving derived from the substitution of cast aluminum is only 11 percent.

Even more striking, the comparison of mild steel and high-strength steel shows that the high-strength material may offer a weight saving in one application and no saving at all in another. High-strength steel and mild steel have the same elastic modulus, which is a crucial measure of stiffness. Hence in building door panels that must meet a certain minimum standard of stiffness, little weight would be saved by substituting high-strength steel for the conventional material. If, on the other hand, structural strength rather than stiffness is needed (as in the case of the side-door beams that protect the occupants from side impacts), high-strength steel could offer a weight saving of 18 percent.

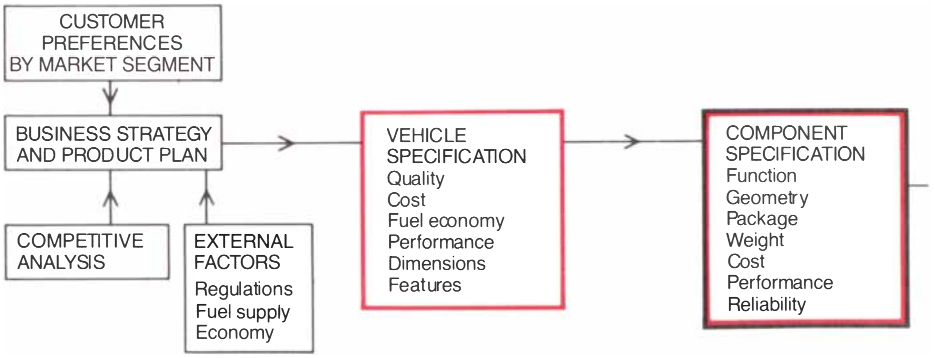
Clearly the physical properties of a material in its specific engineering context have much to do with whether weight can be saved by switching to a "lightweight" material. The process of deciding which material to adopt does not stop, however, when the weight saving has been computed. Most lightweight materials are currently more expensive than the materials they replace. Therefore the saving of weight must surpass a minimum level in order to compensate for the higher cost of the material. Of current lightweight materials, only certain high-strength steels are cost-effective on the basis of materials cost alone.

Yet other lightweight materials such as plastic and aluminum are rapidly finding their way into U.S. automobiles. Why? One reason is that when fabrication costs, component-integration advantages and facility and tooling costs are taken into account, these materials are also seen to be cost-effective. For example, improvements in aluminum-casting processes are reducing fabrication costs and thereby helping to compensate for the high cost of aluminum. Plastics offer advantages in the integration of components: the material is so easy to form that large assemblies, which would require many separate metal parts, can be molded as a single unit from plastic.

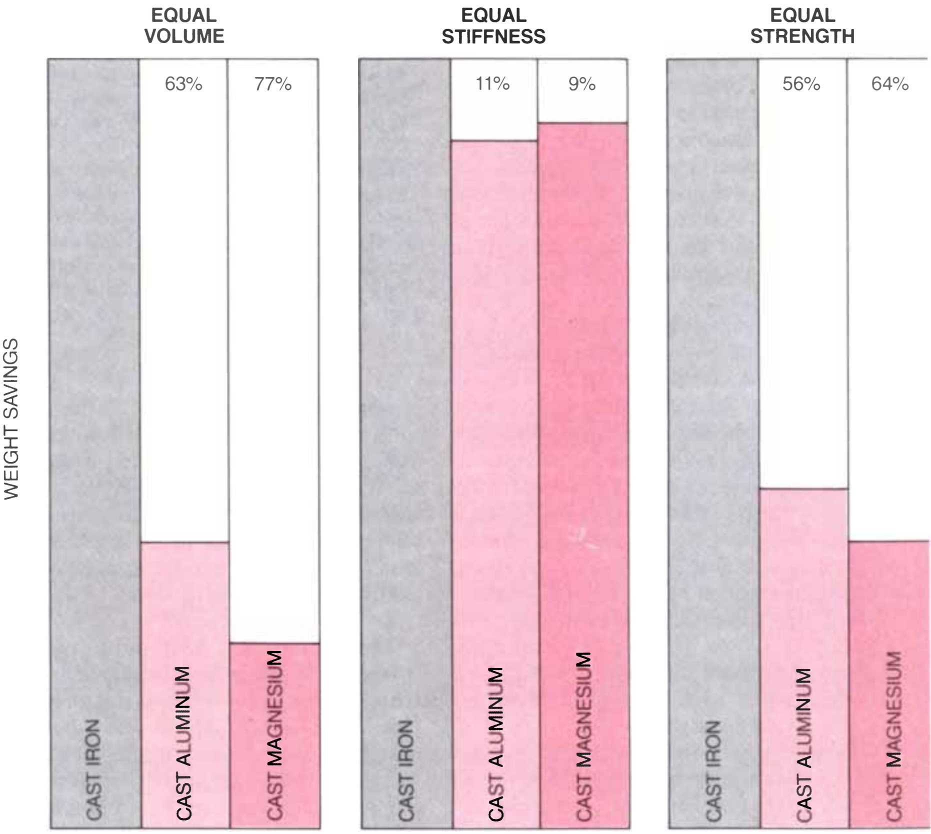
Weighing the fabrication advantages of lightweight materials is only one aspect of the overall scrutiny to which patterns of production are now being subjected in the U.S. automotive industry. The reexamination covers the entire process of fabricating components, from the making of the material to the final finishing. Most manufacturers have not participated in the first stage of materials synthesis, such as steelmaking. Instead they have generally bought primary fabrication forms (examples are ingots, sheets and rods) from suppliers and then manufactured the components; another practice is to buy components ready-made from suppliers.

The major automakers vary considerably in how much they rely on external sources of completed parts and subassemblies. Chrysler currently buys about 70 percent of its parts, Ford 50 percent and General Motors only 30 percent; the rest are fabricated by the manufacturers themselves. In the future these ratios may increase as vehicle manufacturers develop long-term business relationships with suppliers and other vehicle manufacturers. The ultimate form of reliance on external sources is the purchase of complete vehicles, which are offered on the domestic market with the purchaser's nameplate.

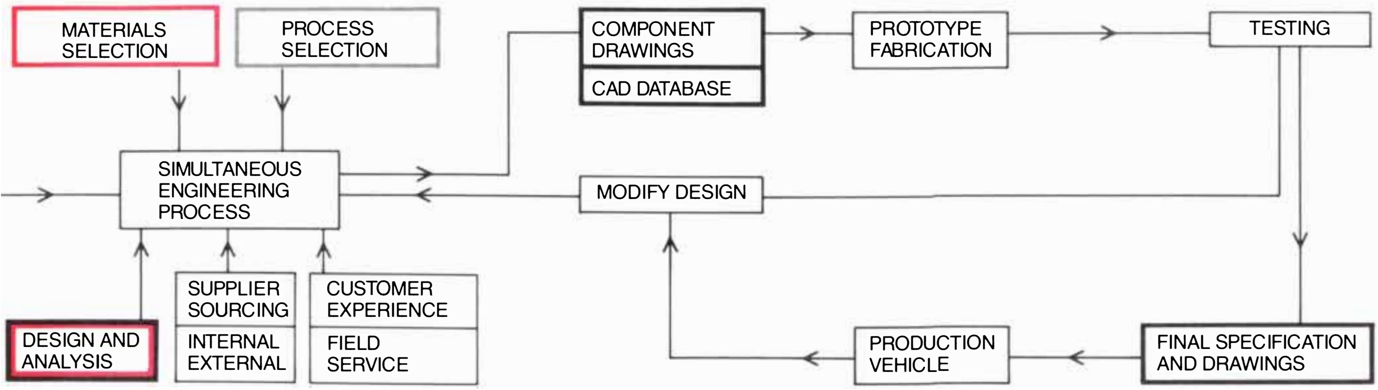
The trend toward reliance on others may soon reach its limit, however, because the desire to reduce costs is balanced by the manufacturers' fear of losing their design, engineering and manufacturing base. The systems U.S. automobile makers build themselves have generally been the major subas-



DESIGN OF AN AUTOMOBILE is a hierarchical process that relies increasingly on computer-aided methods for design, or CAD (*black*), engineering analysis and simulation, or CAE (*color*), and manufacturing analysis, or CAM (*gray*). The process begins with an overall business strategy and product plan that indicate the type of vehicle and its overall specifications, including quality, cost, size, weight and performance. At this stage computer simulations are carried out to ensure that various aspects of the vehicle (such as engine



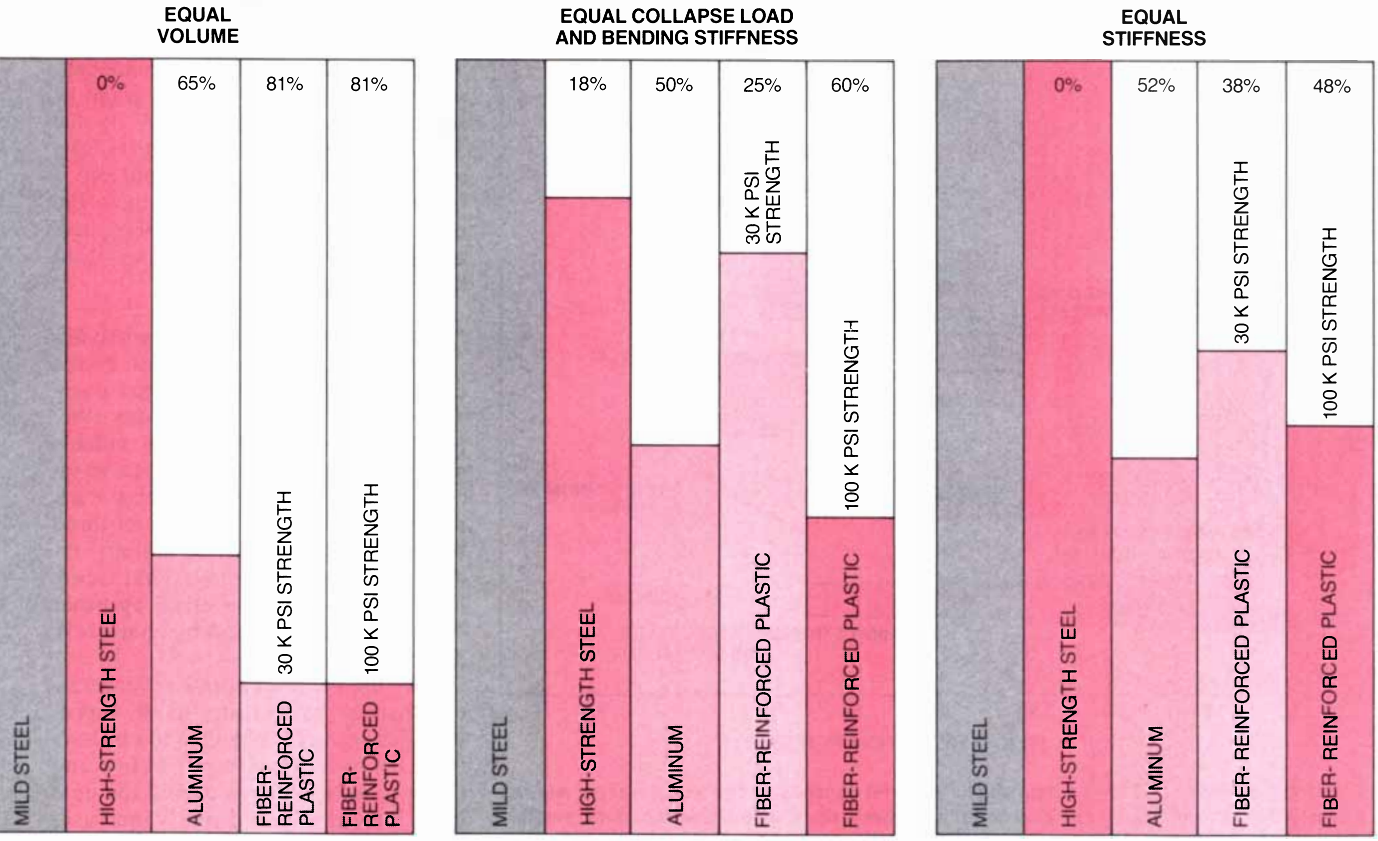
WEIGHT REDUCTION that can be achieved in designing a part by substituting a lightweight material for a conventional one depends critically on the part's function. A unit volume of cast aluminum weighs 63 percent less than an equal volume of cast iron. Cast iron, however, is stiffer than cast aluminum. Therefore if a hypothetical cast-aluminum part is to be as stiff as a cast-iron one, more aluminum would have to be used and the weight saving would be reduced to 11 percent. If equal strength is required in the hypo-



power and fuel consumption) meet their targets. Individual components are then designed, with the overall specifications serving as guidelines. A component's shape is determined by simultaneous consideration of several factors: the part's function, the material from which it will be made and the constraints imposed by the manufacturing process. Other considerations are package (how the part fits with other components), weight and cost. In the past one could not know how well the component functioned until it was fabricated. Computer-aided techniques now make it possible in many instances to predict performance before fabrication. Manufacturing constraints, once also considered late in the design process, now form a significant part of simultaneous engineering.

semblies—body, engine and transmission. If they begin to buy the components of these major subsystems abroad, the technical capacity for designing, engineering and manufacturing competitive products may be lost.

The countervailing tensions that manufacturers experience in deciding how much of each vehicle to buy and how much to build are one example of the complex economic and technological forces that prevail in the U.S. automobile industry. Those forces have combined to bring about dramatic alterations in the materials content of the average U.S. vehicle in the past 20 years. But economic forces have not acted alone. At each stage the effects of consumer preferences and market shifts have been tempered by Federal regulations that govern safety,



thetical aluminum part, the weight saving would be 56 percent. (In actual design situations the weight saving offered by the substitution of aluminum for cast iron ranges from 35 to 60 percent.) Similarly, aluminum and fiber-reinforced plastics are much lighter than mild (ordinary) steel by volume. The weight savings, however, are much smaller if equal stiffness or equal collapse load and bending stiffness (a measure of structural strength) is needed. High-strength steel is no lighter by volume than mild steel, nor is it stiffer. Where structural strength is the main concern, however, high-strength steel does offer a weight saving: 18 percent in this example. The hypothetical examples in the illustration were developed by Christopher L. Magee of the Ford Motor Company.

vehicle emissions and fuel economy.

The history of the materials content of U.S. cars and trucks since World War II can be divided roughly into three periods. In the postwar period, from 1950 to about 1966, passenger cars were fabricated chiefly from mild steel, which during this period formed 68 percent of their content on the average. Cast iron made up 17 percent and alloy bar grades of steel contributed an additional .5 percent. During the postwar period consumers developed a taste for luxurious transport, and options such as automatic transmission, power steering, power brakes and air conditioning added about 200 pounds to the weight of the average passenger car.

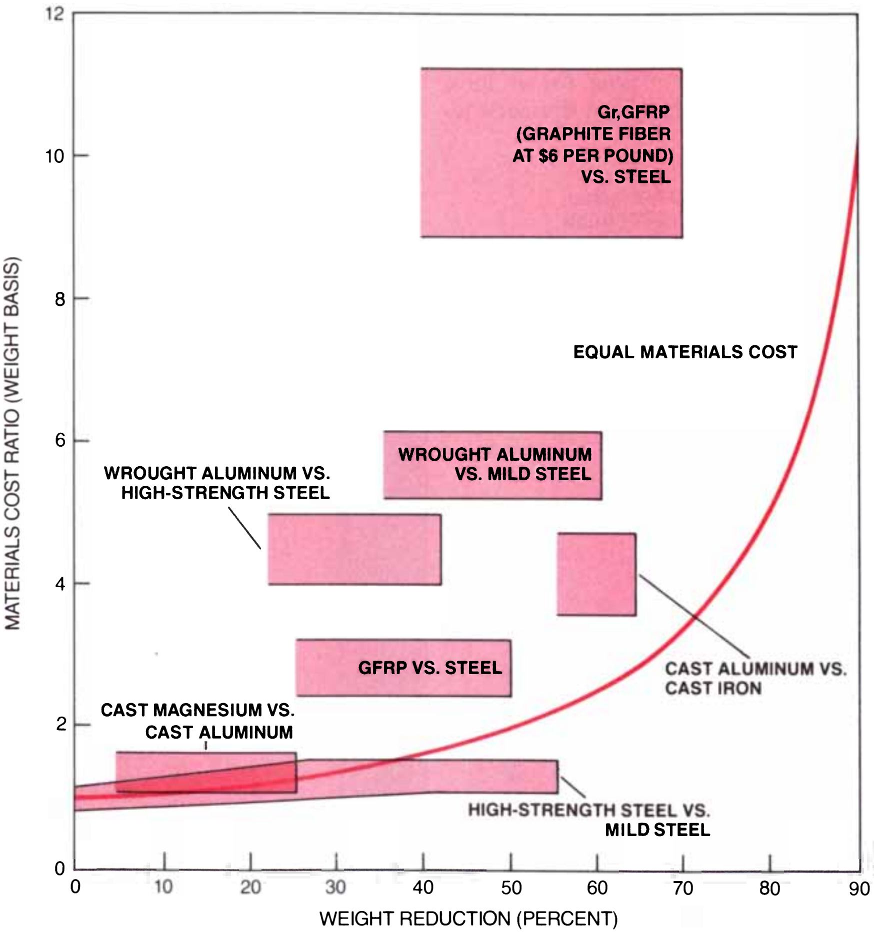
The succeeding period, from 1967 through 1976, was dominated by the impact of Federal regulation; it was then that Government standards began to have a significant effect on the weight and materials content of the average passenger vehicle. The Federal Motor Vehicle Safety Standards, which were established during that time, increased the protection of the driver and passengers, reduced the possible intrusion of the steering column, increased side-door strength and the energy absorption of the bumper systems and influenced the detailed design of many other parts of the car. To meet the new safety requirements many structures were made heavier and new components were added to the vehicle. The result was a further increase in weight. Since the gain in weight led to a decrease in fuel economy, the automobile companies began to explore weight-saving techniques, including increased application of high-strength steels.

Regulations governing how much pollution each car is allowed to emit also influenced materials content, sometimes in surprising ways. For example, in recent times the automotive industry has accounted for from 20 to 35 percent of all the platinum, palladium and rhodium consumed each year in the U.S. The increased use of these precious and semiprecious metals, which come mostly from South Africa, is the direct result of regulations designed to protect the environment. Specifically, the Clean Air Act of 1970 imposed limits on the emission of hydrocarbons, carbon monoxide and oxides of nitrogen in automobile exhaust. The technical response on industry's part was to install a chemical reactor—a catalytic converter—in the exhaust system of each new vehicle.

In 1977 a new, more stringent Clean Air Act was passed and its passage led to the development of more sophisticated exhaust-treatment systems. The new systems included a catalyst with carefully adjusted proportions of certain noble metals (particularly platinum and rhodium), a sensor for measuring the oxygen content of the exhaust and an electronic module for controlling the mixture of air and gasoline in the engine. The quantity of noble metals employed in building catalytic converters has risen rapidly, along with that of two other materials: ceramics and a high-quality grade of stainless steel designated 409 by the Society of Automotive Engineers. The ceramic compound is molded into a honeycomb shape that supports the noble metals, and the stainless steel makes up the converter "can" that houses the reactor.

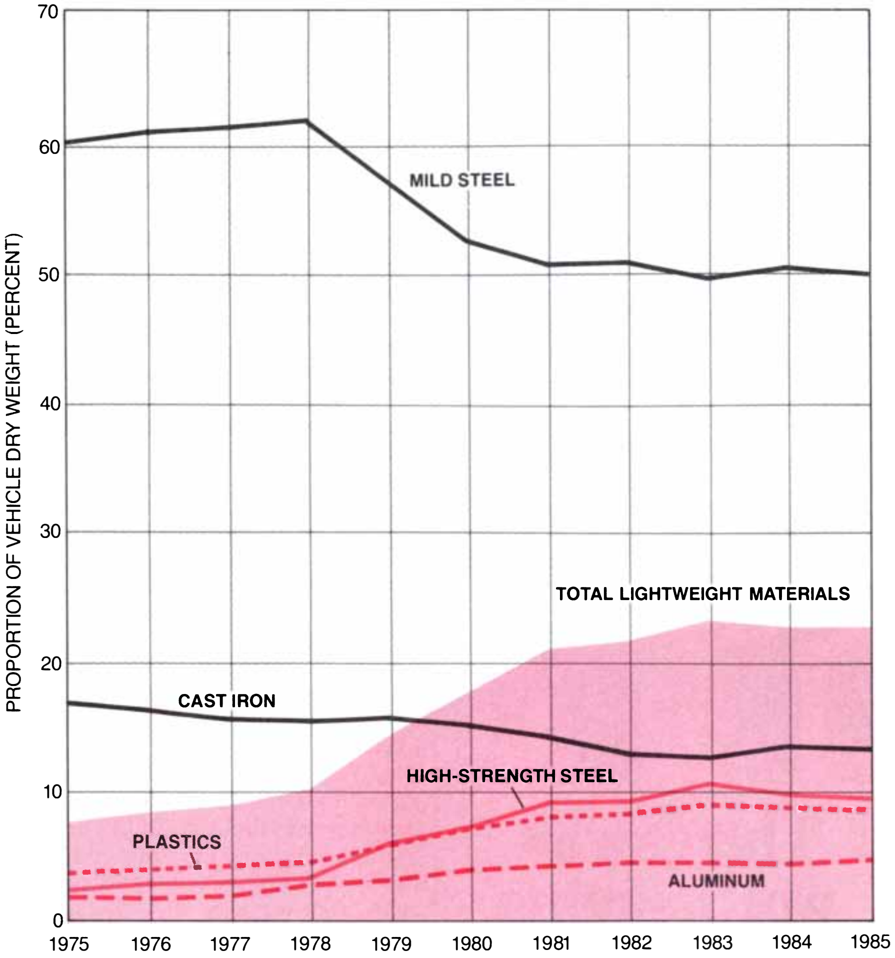
The Federal regulations affected not only the materials content of the catalytic converter but also the overall weight of the vehicle. From 1967 through 1976 the average U.S. vehicle gained about 800 pounds, and the increased weight, combined with the action of the chemical reactors required by emissions laws, led to a sharp reduction in fuel economy. That trend, however, was soon reversed by other Federal regulations and by changes in market forces.

The first oil-price shock reverberated through U.S. industry in 1974, providing a powerful stimulus to improve fuel economy. The Energy Policy and Conservation Act was passed the next year. The act required yearly increases in the average fuel economy of each manufacturer's fleet of vehicles. By 1985 the "corporate average fleet fuel economy" (known in the industry as CAFE) was to reach 27.5 miles per gallon. The stepwise CAFE increments, coupled with the growing demand for



COST OF SUBSTITUTING a lightweight material depends on the weight saving and the prices of the two materials. The horizontal axis shows the weight reduction made possible by each substitution and the vertical axis shows the cost of the lightweight material in relation to its conventional counterpart. (GFRP is plastic reinforced with glass fibers. Gr,GFRP is plastic reinforced with fibers of graphite and glass; the data for that material assume a cost for graphite fiber of $6 per pound, a third of its current cost.) For certain substitutions the two materials will be equal in cost (*colored line*). Most lightweight materials have not yet reached the break-even point; an exception is high-strength steel. In many instances, however, savings in processing and assembly costs for the lightweight material offset the additional cost of the material. The data were compiled by Magee.

fuel-efficient cars, stimulated a massive effort by industry to improve fuel economy, in part by reducing vehicle weight. From 1975 through 1983 the average weight of vehicles in the Ford domestic passenger-car fleet fell by 1,200 pounds, reaching 2,607 pounds at the end of the period. Most of the reduction—about 78 percent—was attributable to downsizing. The rest was accomplished by substitution of lightweight materials.



LIGHTWEIGHT MATERIALS CONTENT of the average U.S. vehicle has increased sharply since the mid-1970's. The data are for a sales-weighted average of the Ford U.S. passenger fleet. Plastics, aluminum and high-strength steel currently account for about a fourth of the dry weight of a Ford passenger car. These lightweight materials began supplanting cast iron and mild steel in U.S. vehicles about a decade ago. Manufacturers were then faced with the weight increases that resulted from technology adopted to meet Federal safety and emissions regulations and with rising fuel costs. In response they decreased the size of their vehicles and also increased the lightweight materials content.

Although it might appear that materials substitution had a relatively minor role in weight reduction, in reality the materials content of the typical passenger car had undergone a striking change by the mid-1980's. Whereas in the 1950's mild sheet steel generally made up 65 percent or more of the weight of the average Ford, by 1985 that fraction had fallen to half. Cast iron declined from about 16 percent to about 13. The place of these conventional materials was taken by cast aluminum (which grew from 2 percent to 6, largely by being substituted for cast iron), plastics (which increased from almost nothing to about 9 percent) and high-strength steel, which, although not in use in 1950, 10 years later made up about 10 percent of the weight of the average passenger car. As a result the total lightweight-materials content of the average Ford car rose from 9 percent in 1975 to more than 23 percent 10 years later.

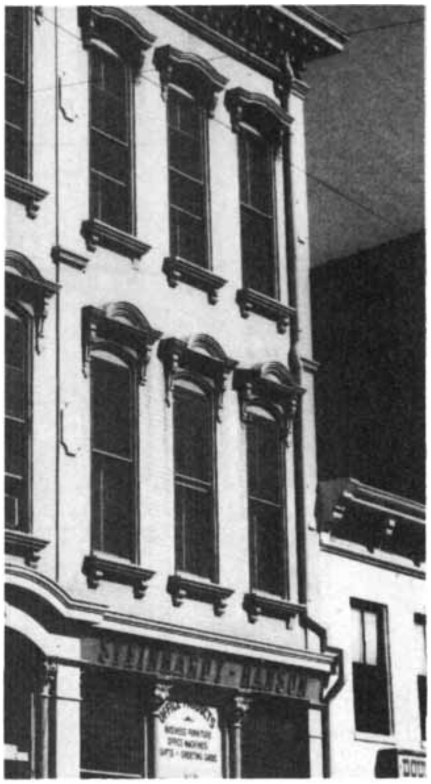
Will such changes continue at the current rapid pace? Although it is difficult to make predictions given the changes that have taken place in the industry in the past two decades, it seems that in the future somewhat less effort will be put into reducing vehicle weight. Fuel costs have declined steadily in the past two years and customers have begun to buy bigger cars again. The cumulative effect of the change in preferences is that the average Ford vehicle (on a sales-weighted basis) has gained back 300 pounds since attaining the minimum weight of 2,607 in 1983.

Yet it should not be assumed that cost and weight reduction have ceased to be significant goals for the automobile industry. Research is continuing on ways to decrease the weight of individual components. For example, the use of titanium to make suspension springs, exhaust valves and valve springs is currently being explored by several manufacturers. Although titanium is an expensive material, it offers weight reductions of some 60 percent over steel. In addition, titanium engine parts reduce friction in the power plant (thereby yielding better fuel economy) and reduce shaking forces (thereby yielding improved engine smoothness).

If the desire to reduce vehicle weight is no longer the predominant factor in the automobile industry, what has taken its place? Several factors are currently perhaps equal in importance to weight reduction. Among them are the trend toward the division of the market into more segments, which entails a need to stress product differentiation, and the worldwide trend toward buying components from suppliers. What is possibly even more significant is the need to compete with Japanese producers in quality as well as cost. The domestic automobile industry has improved the quality of its products in recent years, but further improvement can be expected, a trend that will undoubtedly affect the materials content of passenger cars.

Measures to protect the body from corrosion provide examples of how the effort to improve quality can affect materials content. In recent years the amount of salt put on roads in northern temperate climates has increased dramatically, and as a result automobile bodies are subject to a much more corrosive environment than they were only a decade ago. To improve corrosion resistance, manufacturers have begun to replace mild sheet steel in the body with zinc-coated steels. Such precoated steels now make up about 10 percent of the dry weight of the average Ford vehicle. Indeed, the average car now includes about 10 pounds of zinc in the form of coatings, a figure that is expected to double in five years. Also to protect against corrosion, the amount of stainless steel employed in the exhaust system will probably continue to increase.

The fraction of the vehicle made of plastic will no doubt also grow, owing partly to quality considerations and



partly to the need for tailoring individual products to small market segments. In addition to excellent corrosion protection, plastics offer certain manufacturing cost advantages. Fabrication tooling is cheaper for plastic parts than it is for steel parts and can be changed more easily to accommodate a new style. As a result of these advantages members of the industry are predicting that plastics will be widely employed in automobile bodies and other structures in the next few years. It has been predicted that by 1990 as many as 1.6 million vehicles with bodies made entirely of plastic will be manufactured each year.

If such projections are to be realized, the developmental work now under way on plastic materials will have to sustain its energetic pace. Two different types of plastic are currently receiving considerable attention from the automotive industry. One type is a plastic reinforced with glass fibers. Such fiber-reinforced plastics show considerable promise for making components that must bear heavy loads. The other type is a flexible thermoplastic that can be molded into body panels whose slight flexibility helps to minimize damage in minor collisions. Safety and structural-integrity tests indicate that a plastic body is feasible, and so the high projections now being made may be realistic.

The work being done on plastics is only a fraction of the developmental effort devoted to specific materials by the automotive industry. A considerable amount of that effort is being given to ceramics, both as an addition to other materials and alone. Ceramic particles or fibers can be dispersed in a metallic base, usually aluminum or magnesium, to form what are called metal-matrix composites. Such composites are strong and stiff and show considerable resistance to wear; they are being tested for engine parts and other applications.

Ceramics themselves are of interest because of their low density, low thermal conductivity (which enables them to isolate regions of high temperature) and strength at high temperatures. Extensive research and development is being carried out in many countries, including the U.S. and Japan, on the feasibility of building components for gasoline and diesel engines from ceramics. In gasoline engines ceramics are beginning to appear in turbochargers; in diesel engines they are appearing in glow plugs and prechamber cups. Furthermore, the efficiency of diesel engines can be improved by insulating the combustion chamber with ceramics.

It is likely that within the next decade ceramic components will be utilized much more widely for building both gasoline and diesel engines. In the longer term ceramics could form the basis of revolutionary automobile power plants. The Department of Energy and the National Aeronautics and Space Administration have collaborated to sponsor a development program for an advanced automotive gas turbine. Contracts have been awarded to two competing groups: one to Ford and its partner, the Garrett AiResearch Manufacturing Company, the other to General Motors. The main developmental objective is to build a practical flow path to contain the turbine's hot gases, which can reach a temperature of 1,370 degrees Celsius (2,500 degrees Fahrenheit). Advanced silicon nitride ceramics are being tested for the parts that form the flow path.

Although electronic and magnetic materials are relatively minor in terms of weight content, they play an increasingly important role in advancing the technology level of domestic cars and trucks. In the future every major subsystem of the vehicle (engine, transmission, suspension and steering) will be under electronic control, and a major effort will be made to integrate stand-alone electronic control systems into a single, unified system. A variety of new electronic and magnetic devices may appear on future vehicles, such as silicon-based smart sensors and optoelectronic components, gallium arsenide radar transmitters, amorphous semiconductors, new liquid-crystal materials for displays, and rapidly solidified magnet materials.

Such glittering technological visions should not be allowed to obscure the fundamental changes that have already taken place in the materials from which ordinary passenger cars are made. Although the manufacture of automobiles is based largely on mature technologies, it is subject to strong pressures in the form of foreign competition, changing consumer preferences, changes in fuel prices, Government regulation and technological innovation. Beginning in the mid-1970's those forces slowly but relentlessly began to alter the size, shape and content of cars and trucks. By the mid-1980's the typical U.S. automobile, with its high content of aluminum, plastics and high-strength steel and its low silhouette, was a quite different machine from its recent predecessors. Because of the size of the automobile industry, such changes cannot help but have a significant effect on the overall pattern of materials production and consumption in the U.S.

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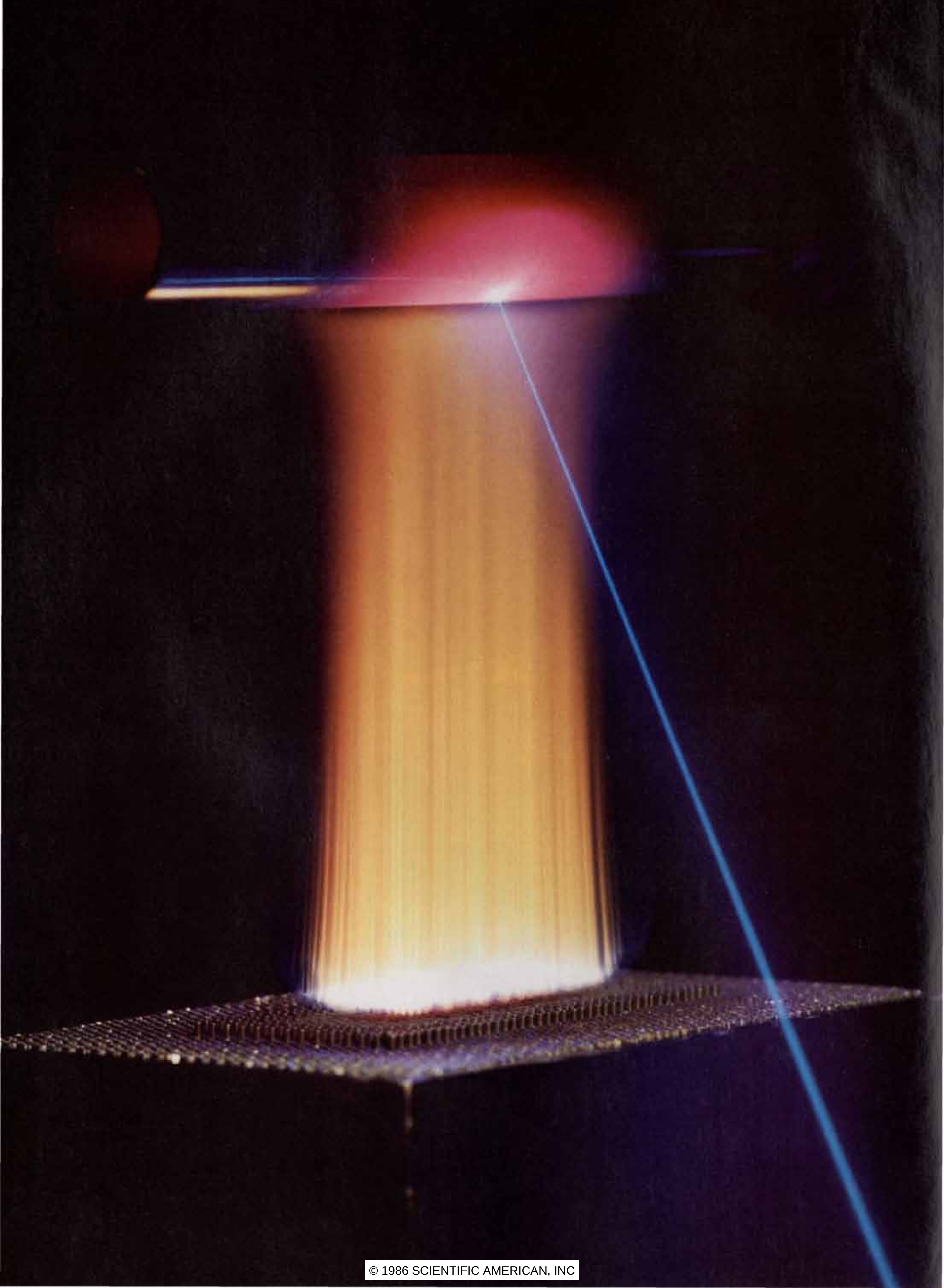


Materials for Energy Utilization

The economic well-being of any modern society requires that energy be captured, converted from one form into another and consumed in myriad ways. Each step demands materials with special properties

by Richard S. Claassen and Louis A. Girifalco

The life of an industrial society is sustained by continual flows of materials and energy. Indeed, the two flows are inseparable. Without the consumption of energy, raw materials could not be reworked, but without the proper materials, the sources of energy could barely be tapped. Every aspect of energy utilization—its extraction, its processing and refining, its conversion from one form into another, its distribution and its efficient consumption—now depends on sophisticated materials tailored, for instance, to catalyze a chemical reaction, absorb sunlight, conduct electricity or resist corrosion and heat.

Innovations in the materials that handle energy are reflected, therefore, in a society's standard of living, because the standard of living depends strongly on the consumption of energy. The dependence is most easily seen by comparing countries that have different rates of energy consumption—in particular, by plotting the gross domestic product against the energy consumption per capita. It then becomes clear that a higher standard of living is closely linked to greater energy consumption. U.S. history supports this correlation. Since 1900 the growth in U.S. energy consumption has far outstripped the growth in population, except during the 1930's, the time of the Great Depression. Meanwhile the efficiency of energy production has greatly improved. In 1899 the average efficiency of producing electricity was 4 or 5 percent; in 1984 it was 33 percent. Whereas the per capita consumption of primary energy sources (such as crude oil) since the beginning of the century has increased more than threefold, the per capita consumption of end-point energy (such as electricity) has increased more than tenfold.

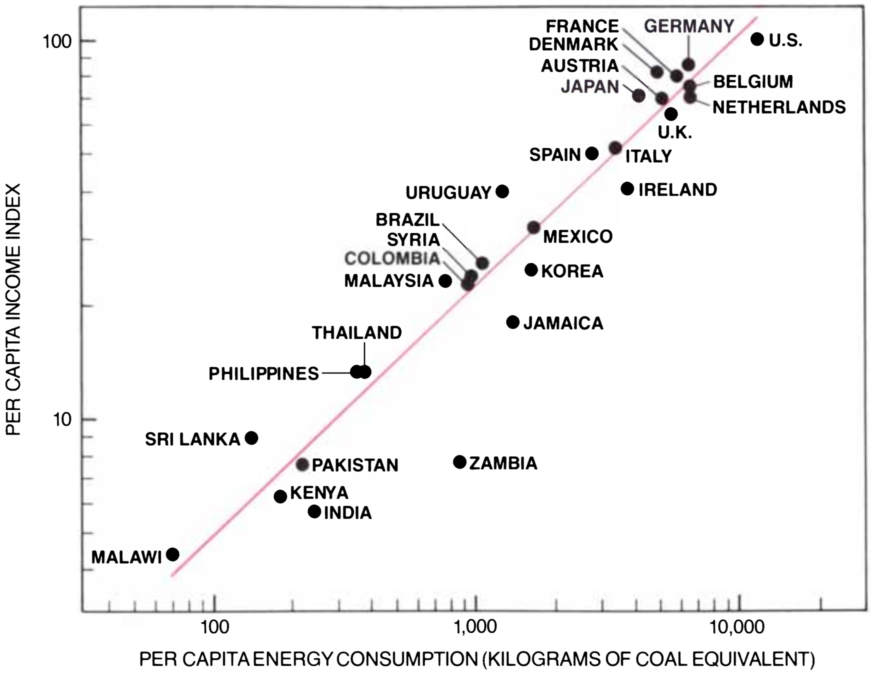
The energy also does more than it used to. In the U.S. the ratio of gross national product (in constant dollars) to energy consumption stayed relatively constant over the first half of the century. Since then it has been increasing: the nation now generates about a third more G.N.P. for each unit of energy consumption than it did in 1970. There are several reasons for this trend. Emerging high technologies such as computers and telecommunications tend to have a low demand for energy. The service sector of the economy is also becoming dominant, and it too is not energy-intensive, compared with the manufacturing and transport sectors. A further reason is surely that innovative materials have facilitated energy conservation and efficient utilization.

How have materials come to be so important in the use of energy resources? Two interlinked answers come to mind. The first is that energy is being exploited in increasingly complex ways. In simpler times the U.S. economy mined coal and burned it directly to produce heat. The economy still burns natural gas after only minor processing. Oil, on the other hand, requires extensive refining before it can be consumed, and electricity is the result of a large-scale conversion of energy resources. For the energy technologies of the future this trend will doubtless continue. Indeed, it is likely that among all the possible new technologies only the solar heating of homes and hot water will directly employ the input energy. All other forms of energy use will require some type of treatment or transformation, such as the liquefaction of coal or the generation of electricity. Materials are pervasive in such transformations.

The material needs of an evolving energy program occasionally are met by the development of a new material. More often the needs are met by the modification or improvement of an existing material. The properties of a material reflect the steps, or processes, necessary to convert the raw substance into the finished product. Steel is an example. It can be wrought (deformed mechanically from an ingot) or cast (solidified in a mold). The resulting properties and performance are very different: the wrought steel has greater strength, the cast steel has lower cost. Much of the effort to devise materials for energy recovery and use has therefore been directed toward developing processes that yield materials whose performance is better matched to the needs of a design.

The second reason for the importance of materials in an energy program is that the development of new materials and the improvement of existing ones have a direct impact on the cost of energy. That impact must be carefully assessed. On the one hand, energy is big business. In 1982 the fos-

EFFORT TO DEVISE MATERIALS to improve the processing of energy is symbolized by this experiment, done at the Sandia National Laboratories in Livermore, Calif., as part of a project intended to alleviate a major problem facing electric utilities: the fouling and slagging of boiler tubes. In a typical utility the hot exhaust from the combustion of fuel such as coal encounters pipes through which water is flowing; the heat turns the water into steam, which drives the turbines that generate electricity. Combustion products deposited on the tubes reduce the transfer of heat to the water. Here particles of pyrite (iron disulfide), a major source of the sulfur in coal, are being "seeded" into a methane-air flame, which heats a tube made of a platinum-rhodium alloy. The beam of an argon-ion laser is scattered by combustion products on the tube; the scattered beam includes light with shifted wavelengths caused by motions (notably vibrations) of the molecules the beam encountered. The beam thus yields a continuous analysis of the accumulating deposits. Such data should facilitate the making of better alloys for steam plants.



CLOSE CONNECTION between energy consumption and standard of living emerges from comparisons of energy use (*horizontal axis*) and purchasing power (*vertical axis*) in 28 countries. The figures were compiled from data for 1979; the calculation of purchasing power was developed by Irving B. Kravis, Alan Heston and Robert Summers of the University of Pennsylvania, who relied on estimates of the actual cost (in local currency) of a long list of goods and services. Although the U.S. economy shows maximal values of energy use and purchasing power, it lies along the trend of the figures (*colored line*).

sil fuel produced in the U.S. was worth \$158 billion, fuel imports cost \$53 billion and consumer expenditures for energy totaled \$418 billion. On the other hand, \$418 billion is a small fraction of the nation's G.N.P. In other words, energy has been cheap. Throughout the first half of this century the cost of mineral fuels (coal, petroleum, natural gas and liquefied natural gas) was no more than 4 percent of the G.N.P. At times it was as little as 2 percent.

Cheap energy is essential for economic growth. In the 1970's the "oil shock" initiated by OPEC, the Organization of Petroleum Exporting Countries, made the cost of fuels (as a percentage of the G.N.P.) increase nearly fourfold, producing the highest relative energy costs in U.S. history. From 1973 to 1975 the G.N.P. per capita decreased: in 1974 it was 8 percent less than it had been in 1973, and it did not regain the 1973 level until 1977. More recently the cost of energy (as a proportion of the G.N.P.) has been decreasing once again as the economy increases its own energy-production efforts and learns to use energy more efficiently. These gains were accelerated by advances in materials.

Solar photovoltaic cells provide an excellent example of how successive innovations in existing materials can lower the cost of energy. The cells, which produce electricity directly from sunlight, have been employed successfully on spacecraft since 1974. On the earth they have exceptional appeal: they do not pollute the environment and they do not deplete finite energy resources. Only the cost of the cells has kept them from making a major contribution to the overall supply of electricity.

One way to compare the costs of solar cells and other systems for generating electricity is to apply a standard economic measure: investment per unit of capacity, expressed in terms of the cost (in dollars) per kilowatt of installed generating capacity. In 1975 coal-fired plants that generate electricity by making steam and employing the steam to drive turbines were quoted at about \$230 per kilowatt and nuclear plants at about \$500 per kilowatt. Solar photovoltaic installations, whose output depends on the ever changing strength of sunlight, are usually assessed in terms of dollars per kilowatt of peak generating capacity. (The yearly average output of a photovoltaic installation in the desert of the U.S. Southwest is approximately a fifth of the peak rating.) In 1975 a flat-plate array of photovoltaic cells (the simplest arrangement) was estimated to cost \$75,000 per kilowatt of peak capacity, or some 300 times the cost of a coal-fired plant. Since the solar-cell array requires no fuel, the comparison is incomplete. Nevertheless, it illustrates how uneconomical the photovoltaic cells have been.

The reason the cells were so expensive lies chiefly in their materials. Early photovoltaic cells were fabricated from large, single crystals of silicon of exceptional purity, grown by a technique (the Czochralski process) in which a small seed crystal is pulled slowly from a reservoir of high-purity liquid silicon, accreting silicon as it progresses. The resulting single-crystal boule (the generic term for a synthesized mass with an orderly crystalline structure) is sawed into thin slices, each about a millimeter thick.

The slices are "doped": they are placed in a furnace so that dopant atoms (controlled impurities essential to the function of the cell) can diffuse into the slices and claim positions in the crystal lattice. Finally, the doped slices are metallized (given metallic leads to carry off the current they produce) and encapsulated (to protect them from the environment). A similar sequence of steps is well suited for the economical manufacture of integrated circuits: a slice 10 centimeters in diameter is enough for hundreds of semiconductor chips, each chip bearing an intricate pattern of circuits. Unfortunately in photovoltaic applications the entire slice yields only one solar cell, whose peak output is about one watt.

The future is rather more hopeful; innovations in the processing of the materials in photovoltaic cells have already reduced the cells' cost. Silicon of ordinary purity (about 99 percent) can now be purified further, to make it suitable for photovoltaic cells, by a technique (the Siemens process) in which the silicon is chemically incorporated into trichlorosilane ($SiHCl_3$) and then converted back into silicon, with impurities left behind. Another technique (developed by the Union Carbide Corporation) converts the silicon to silane (SiH_4) and then reduces it to silicon. Both processes promise to cut the cost of materials for photovoltaic cells in half. Meanwhile the Kayex Corporation has been refining the various stages of the Czochralski process so that boules with a larger cross section can be produced at decreased unit costs.

The innovation likely to have the greatest impact on the cost of materials for photovoltaic cells is the direct growth of silicon crystals in sheets that are suitable almost immediately for fabrication into cells. Two techniques hold promise, although some prob-

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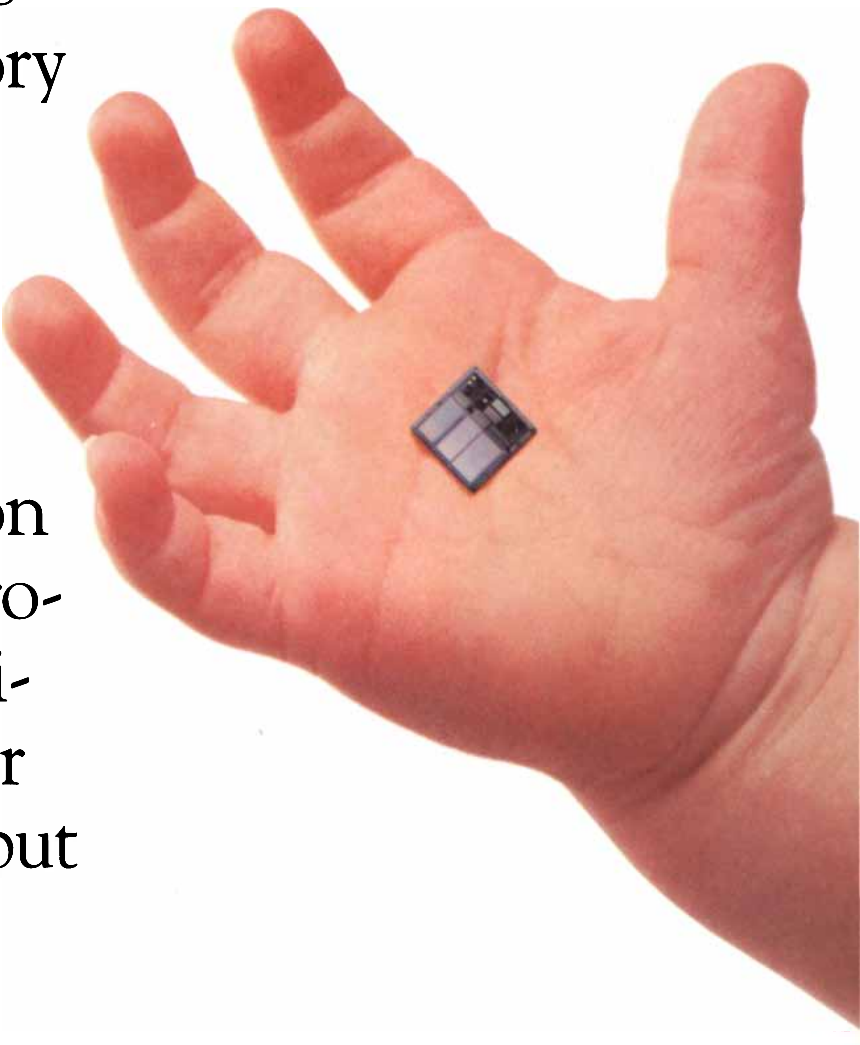

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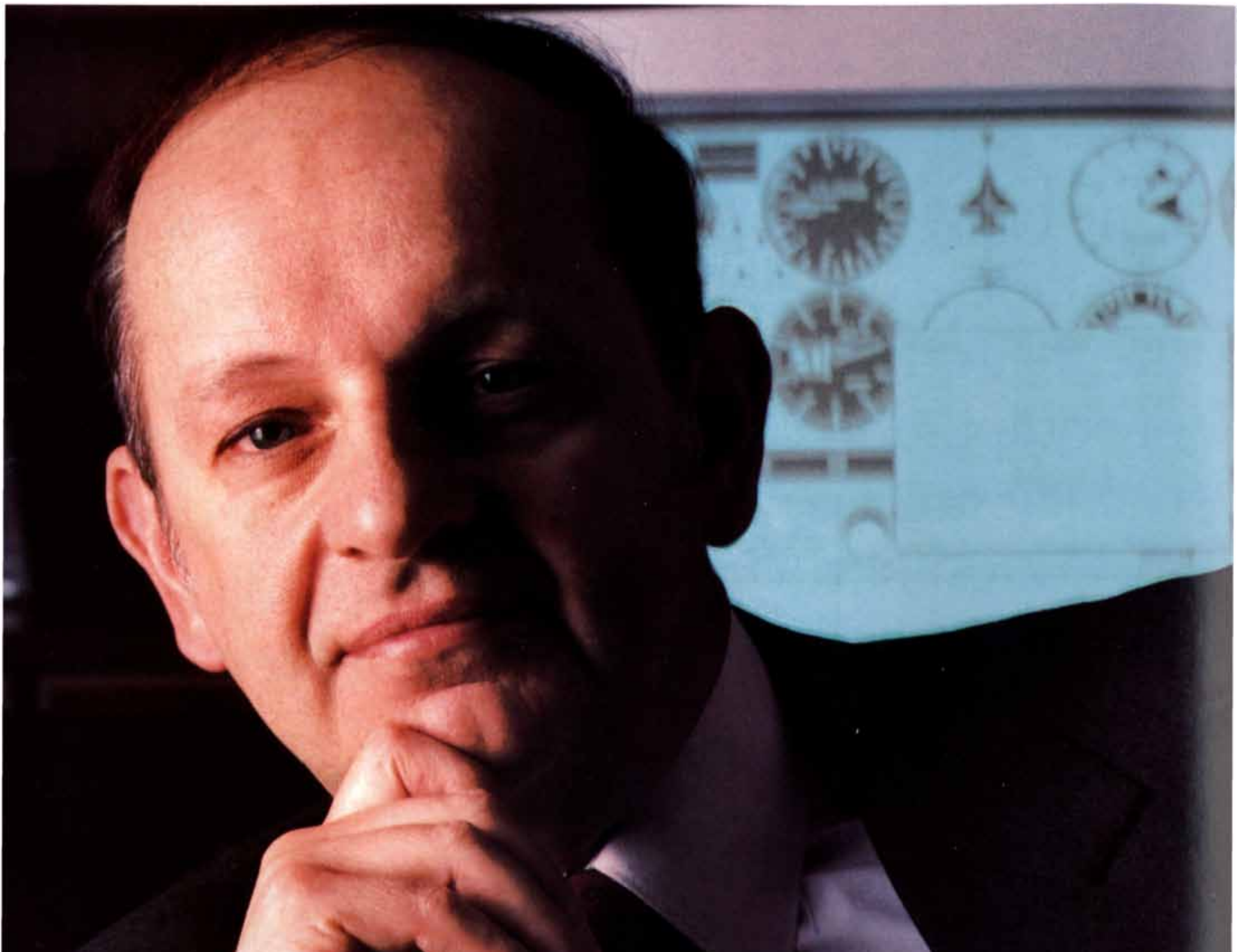

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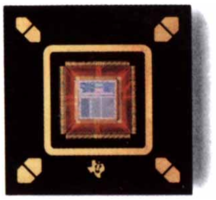

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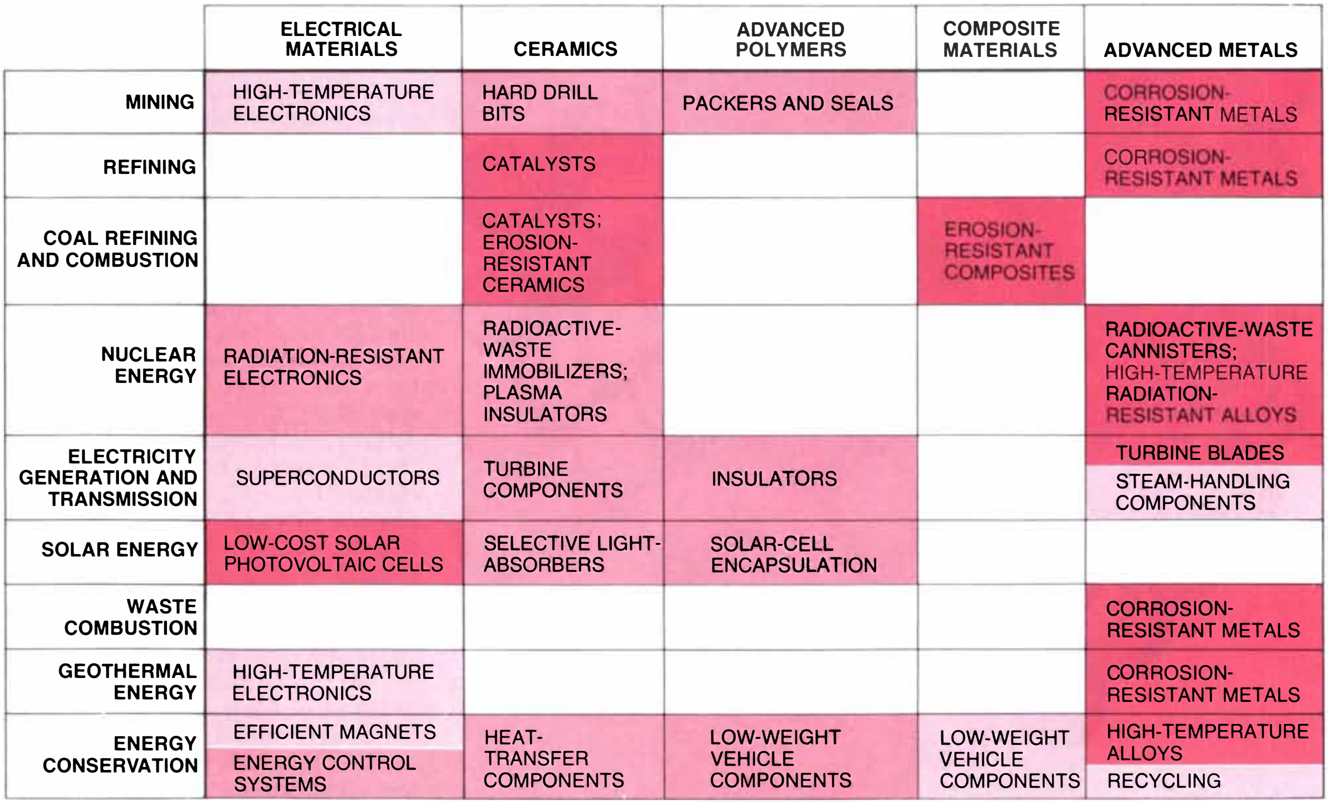
lems must still be resolved. In the first technique, called edge-defined film-fed growth, a single crystal pulled from a melt is constrained by graphite dies so that it forms a single sheet. The problem is that silicon reacts with graphite to make precipitates of silicon carbide. In an effort to eliminate such impurities, the second technique, the dendritic-web process, was invented. In this scheme silicon ribbons called dendrites are grown in a silicon melt under precise control of temperature. The ribbons can then be pulled from the melt without the need for dies. The problem here is the low rate of growth of the ribbons. Better knowledge of material properties such as the creep behavior, or slow deformation, of silicon near the melt temperature will provide some of the understanding necessary for increasing the production rate.

The preparation of silicon accounts, of course, for only a part of the cost of solar photovoltaic cells. In addition the cells must be doped, metallized, interconnected and encapsulated. Refinements in these aspects of the technology have come from a wide variety of developments in materials and in manufacturing processes. Copper rather than silver can now be employed for the metallization; improved encapsulating materials have come into use; the soldering of electrical connections between cells has now been automated. The numerous innovations are reflected in the estimate that in large-scale production a solar photovoltaic array would now cost $1,500 per kilowatt of peak capacity (in 1985 dollars). It is a dramatic improvement over the situation in 1975. During the same 10-year period the cost of a conventional coal-fired plant has increased to approximately $1,100 per kilowatt. Even so, the cost of solar photovoltaics will have to decrease further if the cells are to have a significant impact on energy production.

In addition to their impact on the cost of energy, materials affect the efficiency with which energy is consumed. In all sectors of the economy this efficiency is low. The residential and commercial sectors have a simple efficiency of 65 percent, measured merely by comparing the heat emerging from furnaces with the energy content of the fuel that fires them. The overall thermodynamic efficiency of heating or cooling a building is well under 10 percent. In the transport sector the figure is 10 percent. The industrial sector is the most efficient user: its efficiency ranges from 10 to 35 percent. The efficiency throughout the economy is on the order of 10 percent.

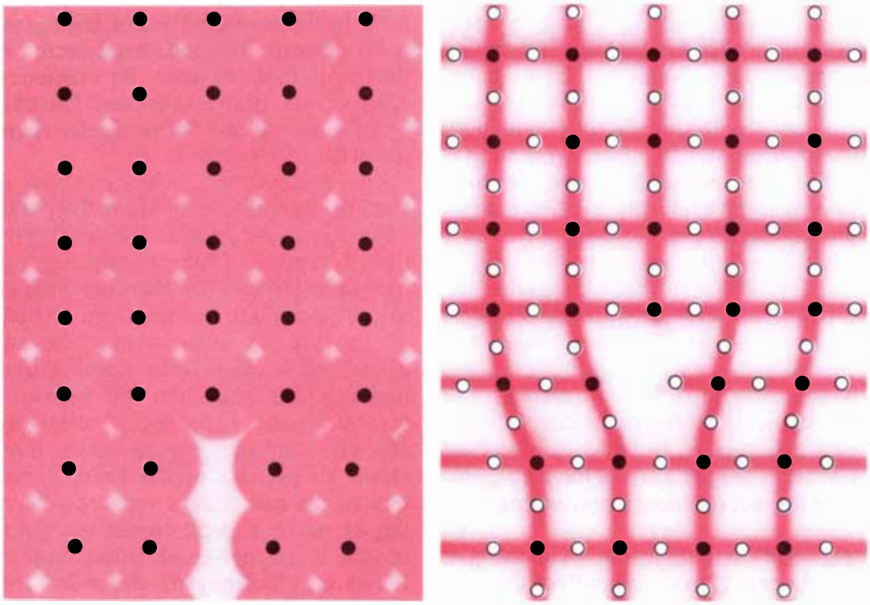
One reason the efficiency is low is that there are losses all along the paths of energy flow. Consider, for example, the efficiencies of the various steps required to convert the chemical energy in petroleum into the mechanical work of moving an automobile. The recovery of crude oil, the refining that makes it into petroleum and the transport of the petroleum are all relatively efficient; cumulatively, however, they claim 19 percent of the energy content of the raw energy resource, leaving 81 percent. Next comes the automobile's internal-combustion engine. It has an efficiency of about 30 percent, reducing the cumulative efficiency to no more than 24 percent. There are further, mechanical inefficiencies between the engine and the final motion of the wheels against the road. The end result is that less than 10 percent of the energy of crude oil actually serves in propelling the car.

Substantial improvements in the efficiency of energy consumption

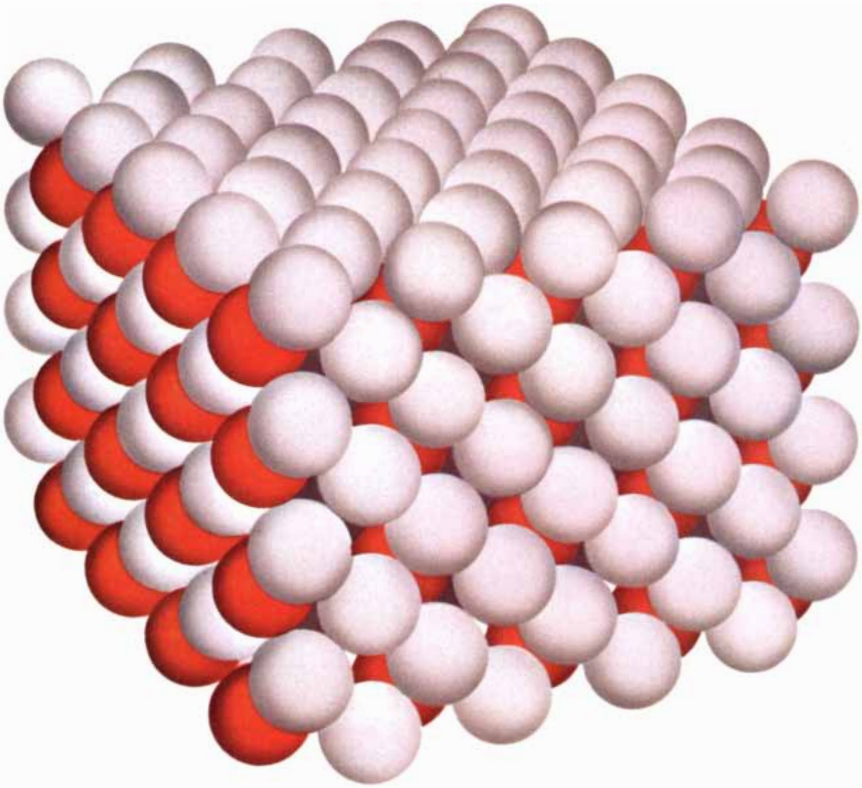


	ELECTRICAL MATERIALS	CERAMICS	ADVANCED POLYMERS	COMPOSITE MATERIALS	ADVANCED METALS
MINING	HIGH-TEMPERATURE ELECTRONICS	HARD DRILL BITS	PACKERS AND SEALS		CORROSION-RESISTANT METALS
REFINING		CATALYSTS			CORROSION-RESISTANT METALS
COAL REFINING AND COMBUSTION		CATALYSTS; EROSION-RESISTANT CERAMICS		EROSION-RESISTANT COMPOSITES	
NUCLEAR ENERGY	RADIATION-RESISTANT ELECTRONICS	RADIOACTIVE-WASTE IMMOBILIZERS; PLASMA INSULATORS			RADIOACTIVE-WASTE CANNISTERS; HIGH-TEMPERATURE RADIATION-RESISTANT ALLOYS
ELECTRICITY GENERATION AND TRANSMISSION	SUPERCONDUCTORS	TURBINE COMPONENTS	INSULATORS		TURBINE BLADES STEAM-HANDLING COMPONENTS
SOLAR ENERGY	LOW-COST SOLAR PHOTOVOLTAIC CELLS	SELECTIVE LIGHT-ABSORBERS	SOLAR-CELL ENCAPSULATION		
WASTE COMBUSTION					CORROSION-RESISTANT METALS
GEOTHERMAL ENERGY	HIGH-TEMPERATURE ELECTRONICS				CORROSION-RESISTANT METALS
ENERGY CONSERVATION	EFFICIENT MAGNETS ENERGY CONTROL SYSTEMS	HEAT-TRANSFER COMPONENTS	LOW-WEIGHT VEHICLE COMPONENTS	LOW-WEIGHT VEHICLE COMPONENTS	HIGH-TEMPERATURE ALLOYS RECYCLING

DIFFERING NEEDS FOR ADVANCED MATERIALS are imposed on the various classes of materials (*top row*) by different energy systems (*left column*); the needs are dictated by the mechanical stresses, temperatures, pressures and chemical environments in which energy systems must function. Instrumentation for mining or for the tapping of geothermal energy will have to resist the high temperatures encountered in the earth's crust; materials intended to confine the plasma, or ionized gas, in a nuclear fusion reactor will have to resist high temperatures and intense radiation. The table gives several further examples. Colors suggest the extent of the effort now under way to devise each needed material: the darkest color marks the most intense developmental efforts.



DUCTILITY, the ability to deform plastically, is more characteristic of metals than it is of ceramics. In a metal (*left*) the outermost electrons in each atom tend to be shared among atoms, producing a delocalized cohesion (*colored shading*). As a result the stress at the sharp edge of a small crack or defect in the material is easy to relieve: a small shearing force is enough to make the defect move. In a ceramic (*right*) the sharing of electrons between atoms takes the form of strongly local and directional chemical bonds (*colored lines*). The motion of a defect requires the breaking of such bonds and the establishment of new ones, so that a force that fails to move the defect can sometimes exceed the fracture strength of the material. Hence a tiny crack can lead to failure under stress. Manufacturing techniques are being developed to produce ceramics extremely free of defects.



NICKEL ALUMINIDE exhibits a remarkable crystalline order in which constellations of nickel atoms (*white*) and of aluminum atoms (*color*) interpenetrate. The order bestows on individual crystals of the alloy a great strength that does not fail at high temperatures. Further processing (the addition of small amounts of boron and the substitution of hafnium atoms for some of the aluminum atoms) yields a polycrystalline form that retains its high-temperature strength. Nickel aluminide is also highly corrosion-resistant; it should help energy systems to function at higher temperatures and thus at greater efficiencies.

should be possible over the next few decades, by means of improved designs and better materials. Fundamentally, the exploitation of energy is a thermodynamic process in which a concentrated energy resource is converted into a useful form of energy, which ultimately is dissipated as low-level heat. The second law of thermodynamics sets a limit on the efficiency of the process. In particular, the maximum fraction of heat energy a given process can convert into work depends exclusively on two temperatures, that of the low-level output (T_2) and that of the concentrated input (T_1). In algebraic terms the maximum fraction is $1 - T_2/T_1$. The idea, then, is to make the input temperature as high as possible while keeping the output temperature low.

The input temperature in any real device is governed by the performance of materials. In a typical coal-fired electricity-generating plant, for example, the temperature of the steam supplied to the turbines is 810 degrees Kelvin (540 degrees Celsius or 1,000 degrees Fahrenheit) and the temperature of the water emerging from the turbines is 370 degrees K. (212 degrees F.). Hence the maximum efficiency is 54 percent. Losses in an actual plant reduce the efficiency to a practical value of about 35 percent. Much of the effort being expended on materials for electricity-generating plants is aimed at devising materials to withstand operating temperatures higher than the ones that are typical today, so that the thermodynamic limit on efficiency can be more advantageous.

One specific long-term avenue to greater thermodynamic efficiency is offered by ceramic turbine blades. Ceramics such as silicon nitride (Si_3N_4) and silicon carbide (SiC) are stable for long periods at temperatures exceeding 1,200 degrees C. The problem is lack of ductility. A ceramic cannot deform plastically: it cannot flow, or "heal," around a small flaw or crack. Hence long service at high temperature and great mechanical stress could lead to blade failure. New methods are being developed to accommodate this limitation. For example, extensive work is being undertaken on manufacturing processes such as the hot-pressing (or sintering under high pressure and temperature) of silicon nitride. The efforts should yield ceramics incorporating a minimum of flaws. Before such materials can serve in actual plants, where a long working life is required, they will need long-term evaluation under pressures, temperatures and a corrosive environment typical of the conditions in which they will serve.

Another avenue to high operating

temperature and thermodynamic efficiency is offered by an intermetallic alloy: nickel aluminide (Ni_3Al). The interest in it derives from its orderly, long-range crystal structure. Atoms of the two component metals, nickel and aluminum, do not intermix at random. Instead an array takes form in which two sublattices, a constellation of nickel atoms and a constellation of aluminum atoms, interpenetrate. The result is a highly stable material resistant to corrosion and oxidation and strong at high temperatures. Its yield stress (the load under which permanent deformation first occurs) actually increases with temperature.

What has kept nickel aluminide from widespread application is that the commercial, polycrystalline form of the alloy has low ductility. Fractures develop between the individual crystalline grains before the grains themselves can deform and heal the flaw. Recent work shows that the careful control of the proportions of nickel and aluminum and the addition of a small amount of boron, in a process called microalloying, increase the cohesion among the grains to such an extent that fractures, when they occur, develop inside the grains. In addition the work shows that the substitution of hafnium for some of the aluminum in the alloy greatly increases the alloy's strength and places the maximum yield strength at a temperature of 850 degrees C. The result is a material that should prove effective in many situations where high operating temperature facilitates greater efficiency. In electricity-generating plants the candidate applications include turbine blades, heat-transfer units and high-pressure piping.

This is not to say that all the possibilities for greater efficiency in energy utilization lie at increased temperatures. At least one possibility is at the opposite extreme: the ultralow temperatures at which certain materials become superconductors and cease to offer resistance to the flow of electric current. A specific possibility lies in superconducting cables: current-carrying strands of a superconductor refrigerated so that its temperature is less than its critical temperature (the temperature at which a given superconductor becomes superconductive). The electric power now carried by massive power lines strung between high towers could be carried more efficiently by much smaller superconducting cables. The added expense and the need for refrigeration might be justified in large urban areas or where the overhead transmission of electricity is proscribed.

STRATAPAX, which improves the performance of drill bits employed in oil and gas drilling, consists of small diamonds sintered, or heated without melting, to form an extremely hard, strong, polycrystalline material that lacks the weak cleavage planes characteristic of natural diamond. The material was developed by the General Electric Company; thin plates of it (*dark gray*) are bonded to tungsten carbide studs, which are mounted on the bit. The rotation of the bit then enables the stratapax to mill away rock. In medium-hard formations a stratapax bit drills four times as fast as traditional bits; moreover, it lasts longer. Annual savings in the U.S. drilling industry are estimated to be several hundred million dollars. Stratapax is an instance of a new material developed in order to facilitate energy production; most innovations involve the improvement of an existing material.

The broad class of materials known as type-II superconductors (because they share certain magnetic properties) are of interest for superconducting cables; they can support currents whose density exceeds 10,000 amperes per square inch of the cable's cross section. The type-II superconductor niobium-titanium (NbTi) is of particular interest because it can readily be drawn into fine wires. Niobium-titanium, however, has a critical temperature of 9.5 degrees K. (9.5 degrees above absolute zero). It would be valuable to use a superconductor whose critical temperature is higher, since the refrigeration of such a material would be easier and costs and consumption of energy would be reduced correspondingly. Niobium-tin (Nb_3Sn) has a critical temperature of 18.1 degrees K. To minimize the cost of making it into cables a process has been developed in which pure niobium is drawn into ribbons. The ribbons are dipped in tin; then a chemical reaction at high temperature produces niobium-tin. In the final step of the process the brittle ribbon is sandwiched between normal conductors.

To yield a practical cable (a bundle of superconducting filaments), some further steps are required. For one thing, the bundle of filaments must be wrapped in an insulator. The conventional insulator, oil-impregnated paper, is unsuitable at extremely low temperatures. An alternative is being developed: some laboratory samples of polypropylene plastic have demonstrated properties that are excellent for a low-temperature insulator. At ambient (or unexceptional) temperatures the samples are flexible, which facilitates installation. At low temperatures the samples exhibit a low dielectric loss, that is, they insulate well. In a kind of feedback that often occurs in technology, the samples have been shown to have superior characteristics for the insulation of normal conductors at ambient temperatures. Nevertheless, an effort will be needed to transfer the capabilities of polypropylene formulated in the laboratory to polypropylene manufactured commercially. A process will have to be devised that yields quantities of the plastic sufficiently free of the impurities that compromise the material's ability to insulate.

Still another way materials affect the use of energy is by improving the reliability and safety of energy production and conversion. Reliability is the result of a good design, thoroughly analyzed and tested and based on materials whose properties under operating conditions are well understood. Safety results from materials developed for a specific need and examined for their performance in all operational situations, even improbable extreme ones. Safety has become increasingly important; the public expects energy technology to have virtually no likelihood of an accident.

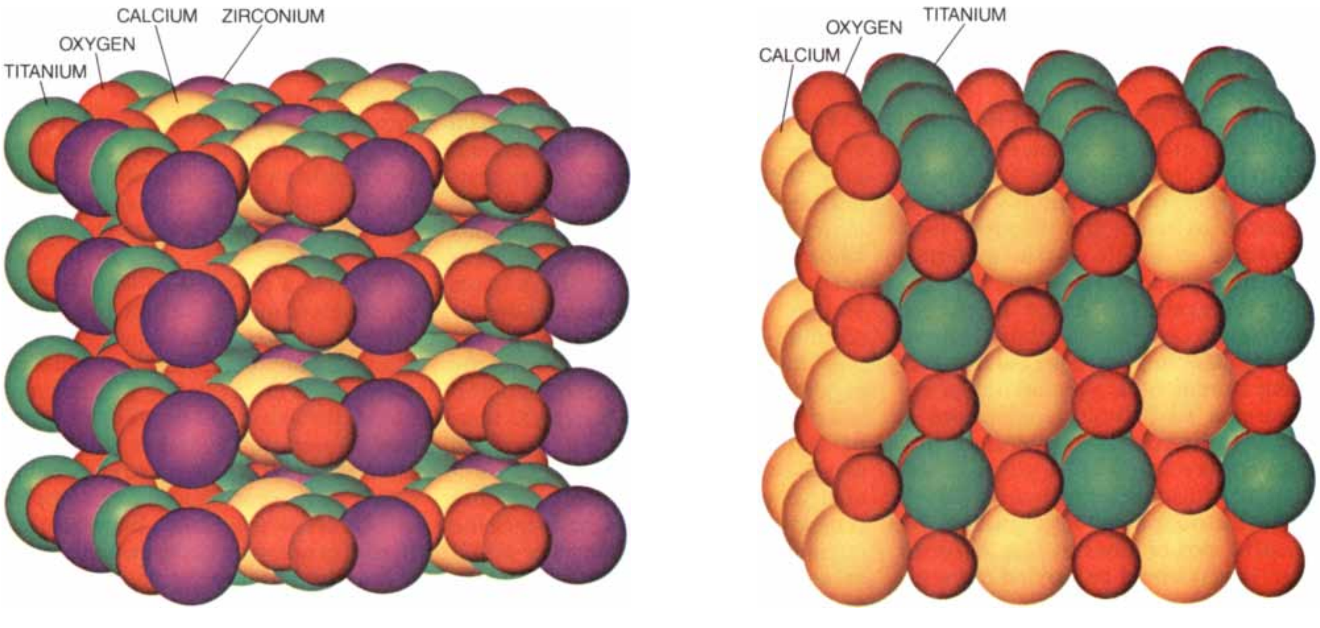
The disposal of radioactive wastes from nuclear reactors will call for such technology. The general strategy for permanent disposal invokes a succession of three steps. First, the waste is to be made an integral part of a relatively insoluble solid. Next, the solid is to be enclosed in an impermeable barrier. Finally, the waste in its enclosures is to be buried in a dry and stable geologic structure. The first two steps require the development of materials.

The work is well under way. For instance, borosilicate glass has been shown to be an excellent host for radioactive waste, that is, an excellent material for the first step in waste disposal. If an even better host is needed in the future, it may turn out to be a ceramic. Indeed, in 1978 Alfred E. Ringwood of the Australian National University proposed a specific ceramic when he suggested that SYNROC—synthetic mixtures of minerals such as zirconolite ($CaZrTi_2O_7$) and perovskite ($CaTiO_3$)—be employed as a trap for radioactive atoms. The natural versions of these minerals are extremely insoluble and are known to have sequestered atoms of radioactive elements including uranium and thorium for periods of hundreds of millions of years. The manufacture of SYNROC, from compounds that include titanium oxide and zirconium oxide, is relatively straightforward. Tests confirm its great stability. The overall challenge is to devise the material best suited to stabilize the mixtures of radioactive elements in various forms of waste.

The second step in waste disposal, the provision of an impermeable barrier between the waste and the environment, demands a cannister highly resistant to corrosion and degradation. The need arises in part because the rates at which chemicals attack a material tend to increase with temperature, and the radioactivity of cesium and strontium will keep the cannister hot for some 300 years. (The cannister's initial temperature, when the radioactivity is at its most intense, will be about 200 degrees C.) A thorough understanding of the cannister's mechanisms of degradation will be required if the cannister's long-term behavior is to be predicted from short-term tests. The intent is to place the cannister in a dry environment. Nevertheless, the cannisters are evaluated by immersion in brine, which represents the worst (namely the most corrosive) surroundings possible.

A titanium alloy designated Ti code 12 is currently being evaluated as a material for the cannisters. The alloy has been shown to develop (on exposure to air) an oxide film that confers protection against corrosion. Exhaustive tests establish, moreover, that the alloy is stable against general and localized corrosion, even at high temperature and under the bombardment of gamma radiation, which would penetrate a cannister. More work is needed to make the alloy suitable for the transportation of waste-filled cannisters to their disposal site. An accident during transportation might crush a cannister, and the properties that must be evaluated in judging the ability of a cannister to resist such an accident are mechanical and structural ones.

On the broadest scale, the development of new or improved materials enables a society to alter its mixture of sources of energy. The ancient



STRUCTURE OF TWO MINERALS, zirconolite (*left*) and perovskite (*right*), inspired the suggestion that synthetic mixtures of minerals might aid the permanent disposal of radioactive wastes. The two are extremely insoluble. In addition they are known to sequester atoms of the radioactive elements uranium and thorium for geologic spans of time. The idea, advanced by Alfred E. Ringwood of the Australian National University, is to incorporate wastes in such minerals; radioactive atoms could substitute for zirconium in zirconolite (*purple*) and for calcium in perovskite (*yellow*). The minerals could then be sintered to produce a ceramic.

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The experts report excellent performance. Simply switch PASSPORT on and adjust the volume knob. Upon radar contact, the alert lamp glows and the variable-pulse audio begins a slow warning: "beep" for X band radar, "brap" for K band. Simultaneously a bar graph of Hewlett-Packard LEDs shows radar proximity.

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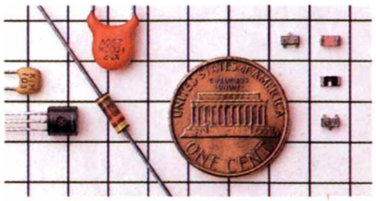

In PASSPORT, 102 SMDs (right) do the work of ordinary transistors, resistors and capacitors.

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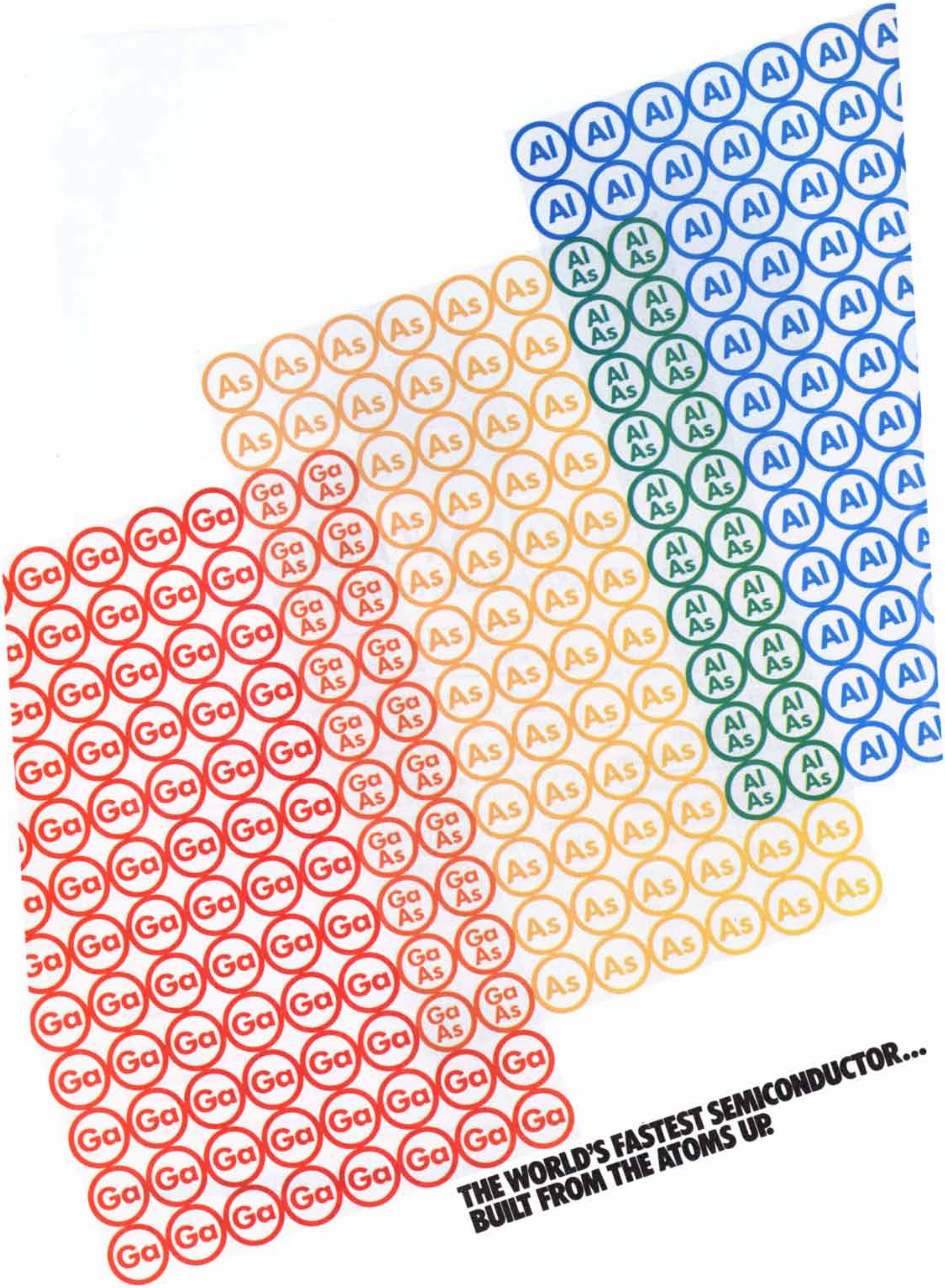
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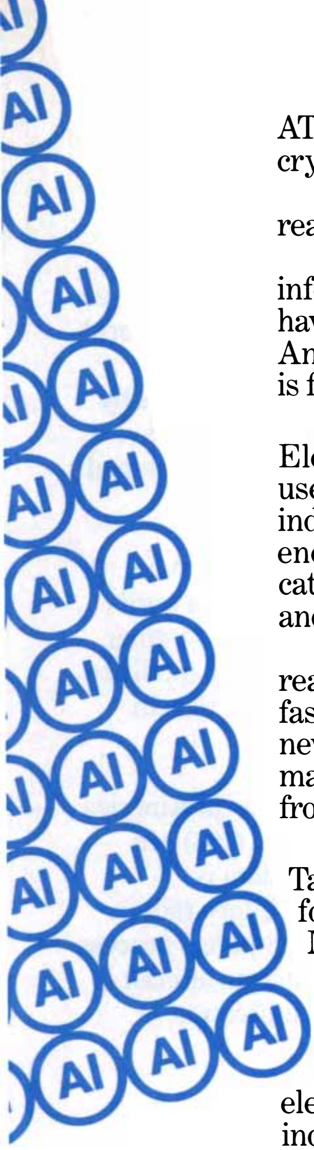


AT&T is building semiconductor crystals atomic layer by atomic layer.

The reason? To help electrons reach their full potential.

In our world of rapidly increasing information needs, the more data we have, the faster it has to be processed. And today, the key to faster processing is faster electrons.

Speed Is Of The Essence

Electrons in silicon—the most widely used material in the semiconductor industry—move quickly. But not quickly enough for many increasingly sophisticated applications, like real-time speed and image processing.

Now, silicon has just about reached its electron speed limit. For faster electrons to meet special needs, new materials are the key—new materials, not found in nature, built from the atoms up.

Going Flat Out With Atoms

Tailor-making new materials uses a form of atomic spray painting called Molecular Beam Epitaxy (MBE).

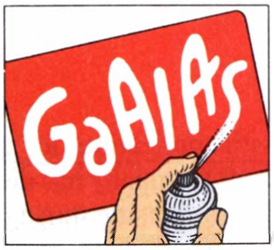
Invented and perfected by AT&T Bell Laboratories scientists, MBE creates ultra-thin, extraordinarily uniform films of selected elements. To prevent contamination, individual layers are sprayed onto a substrate in a vacuum containing 100 billion times fewer atoms than in the earth's normal atmosphere.

Finished films are uniformly flat to plus or minus one atom in depth.

Electrons That Move Like Rockets

In one application, AT&T constructed material using crystal layers of gallium aluminum arsenide and gallium arsenide. The gallium arsenide was kept pure, while the gallium aluminum arsenide layer was seeded, or doped, with carefully controlled impurities—sources of needed electrons.

These electrons are drawn in droves to the face of the pure layer. Here, unimpeded by impurities, electrons can rocket across the transistor's gate at 20 million centimeters per second—almost three times as fast as in today's silicon semiconductors.



Spray painting with atoms.

Using this new material, AT&T scientists collaborated with colleagues at Cornell University to set a transistor speed record. The device switched a logic circuit on and off in 5.8 picoseconds (trillionths of a second)—that's 170,000,000,000 times in a single second.

Putting The Future On The Beam

Molecular Beam Epitaxy has also enabled Bell Labs to produce a semiconductor that replaces electricity with... light.

Built of 2,500 precise, alternate layers of gallium arsenide and gallium aluminum arsenide, the chip contains four photonic switches that are turned on and off by light beams, much the way electronic transistors are activated by electrical charges.

This light switch presages a day when optical computers will process information 1,000 times faster than present electronic computers. A day brought closer by AT&T's layered technology.

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In pioneering work with applications for space-based defense systems and the next generation of missile seekers, Hughes Aircraft Company has demonstrated an advanced infrared sensor. The device is believed to be the world's first high-density, staring, long-wavelength infrared focal plane array (FPA). The hybrid chip, smaller than a fingernail, is integrated with optics and electronics to create TV-like images of a scene, even in total darkness. Unlike conventional infrared sensors, which mechanically scan a scene by means of oscillating or rotating mirrors, the FPA stares at a scene in its view at one time. It promises significant performance, size, weight, and cost benefits over ordinary sensors. The device was developed for the Defense Advanced Research Projects Agency as part of Strategic Defense Initiative efforts.

Programmable software formats within a night vision system for helicopters allow new features to be added as needed to meet new threats. The Hughes Night Vision System (HNVS) is a low-cost, forward-looking infrared system that provides excellent imagery and object detection day or night in all weather. It has extensive built-in test and fault isolation test capabilities. Among the features that may be modified to meet specific requirements are flight symbology, navigational data, automatic set-up mode, system status data, and push-buttons around the display face.

From Alaska to Florida, from Labrador to Hawaii, a new air defense system helps protect North America by watching the skies far beyond U.S. and Canadian borders. The Joint Surveillance System (JSS) can detect attacks from space, by aircraft, and by missiles launched from submarines. The system is comprised of eight regional operations control centers that tie into existing civilian and military radars. Each center receives radar data through a communications network with 285 circuits. Computers process information, prepare it for display consoles, and compare it with known flight plans. When an aircraft is classified as unknown, fighter interceptors scramble and are directed to make visual identification. Hughes developed and built JSS for the U.S. Air Force.

F-4F Phantoms equipped with the same radar carried by F/A-18 Hornet Strike Fighters will maintain their effectiveness through the end of the century. The AN/APG-65 radar is an all-digital multimode system designed for both air-to-air and air-to-surface missions. In air-to-air operations, the Hughes radar will give the Phantom a clean radar scope in either look-up or look-down attitudes. It will also provide track-while-scan capability, long-range search and track, and close-in combat modes. The all-weather sensor will make the aircraft fully AIM-120 AMRAAM capable. Hughes is under contract from Messerschmitt-Boelkow-Blohm for the definition phase of West Germany's F-4F Improved Combat Efficiency program. The company will also work with AEG-Telefunken on the program.

A broad spectrum of technologies, many of which grew up within the past five years, are represented in the products of Hughes' Industrial Electronics Group. Seven divisions and two subsidiaries, each operated like a small high-tech company but backed by resources of its multibillion-dollar parent, offer career benefits to qualified engineers and scientists. Advancing technologies such as microwave and millimeter-wave communications, silicon and GaAs solid-state circuitry, fiber optics, and image processing equipment are pursued in facilities located in many of Southern California's most desirable coastal communities. Send your resume to B.E. Price, Hughes Industrial Electronics Group, Dept. S2, P.O. Box 2999, Torrance, CA 90509. Equal opportunity employer. U.S. citizenship required.

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sources—muscle, wood, water and wind—are the first to be supplemented. They cannot provide the high volume of concentrated forms of energy an industrial society requires. In U.S. history, for example, the industrial expansion that followed the Civil War was possible only because mineral fuels were becoming the primary energy sources. By 1910 coal accounted for three-fourths of U.S. energy consumption. Today oil and gas provide the bulk of our energy.

In brief, it took more than 60 years for coal to become the dominant fuel and a similar period for oil and gas to supersede coal. Energy systems are large and complex; decades must pass before a new energy source can make a significant contribution.

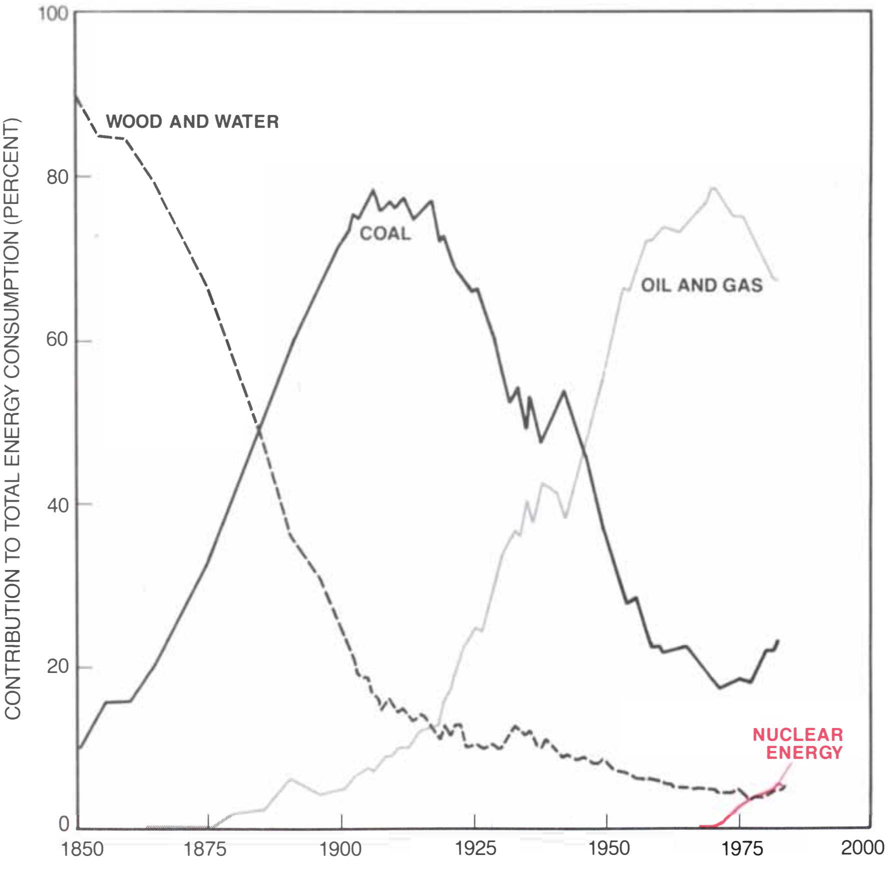
This time scale will also hold true in the future. Precise predictions are subject to differences of opinion. It is clear, however, that the contribution from petroleum will decline and that renewable sources such as sunlight and wind (exploited by photovoltaics and windmills) will have an increasing role. Contributions from nuclear power (fission and fusion) can also be foreseen. All these sources will contribute mostly to the generation of electricity. The greatest remaining need will be liquid fuel suitable for the transportation sector. The conversion of coal into a liquid form appears now to be the most promising approach. The need for specialized materials to facilitate such conversion centers on the effort to devise the appropriate catalysts.

Coal liquefaction was developed six decades ago. In essence it requires the addition of hydrogen to coal by means of a chemical reaction. The result is various liquids, including gasoline, depending on the amount of hydrogen added. A fortunate aspect of the procedure is that the addition of hydrogen displaces most of the sulfur in the coal, which is bound into organic compounds or is present as iron disulfide. The direct reaction of hydrogen and coal requires high temperatures and pressures, which in turn require massive reaction vessels made of expensive materials. Catalysts that promote the reaction under less severe conditions are therefore the key to the economical production of liquefied fuel. The catalysts available today are not as good as they might be: approximately half of the estimated capital cost of a commercial-scale coal-liquefaction plant can be attributed to reaction vessels and their ancillary equipment. Improvement in the selectivity and effectiveness of the catalysts would allow the liquefaction process to take place at reduced temperatures and pressures and could reduce the cost significantly.

An example of the efforts being made to devise better catalysts is given by work on hydrous oxides of titanium, niobium, tantalum and zirconium. These compounds act as supporting structures for catalytic metals such as palladium, platinum, molybdenum or nickel. In particular the compounds can participate in an ion exchange in which a metallic ion in the compound (for instance a sodium ion) is replaced by a catalytic ion (for instance platinum). Subsequent processing yields small clusters of the compound, now incorporating an even distribution of catalytic ions.

The clusters indeed show a potential for dramatically reducing the temperature and pressure required in the first step in coal liquefaction: the hydrogenation of the crushed coal carried in a hydrocarbon solvent. The long-term stability of the catalytic clusters remains in question. Catalysts, by definition, are not consumed by the chemical reaction they facilitate. They are, however, subject to deactivation by chemicals in coal, particularly sulfur. The catalyst must then be reactivated or replaced. Alternatively, the catalyst must be devised to resist deactivation. The ion-exchange process enables the clusters to incorporate different types of active ions in any wanted proportions. This flexibility in the manufacture of the clusters may well make possible the development of catalysts with long life.

The contributions that materials have made, and will continue to make, to the recovery, processing and utilization of energy are crucial to an industrial economy; the history of such economies demonstrates a close relation between energy consumption and standard of living. We are optimistic that further innovations will make energy available in quantities adequate for the continuing improvement of economic well-being in the U.S. and throughout the world.



RISE AND FALL of the contributions made to the U.S. economy by various sources of energy shows that a period of decades is required for each new source to make a substantial contribution. For example, it took decades for coal to supersede wood, wind and water. The need for time will doubtless be true of future sources, such as solar photovoltaics or nuclear fusion. Yet as oil and gas are depleted new sources will have to be found. Specialized materials will be essential in developing these sources. Today's most controversial energy source, nuclear fission, supplies only 5 percent of U.S. energy demand.

Materials for Medicine

New polymers, ceramics, glasses and composites are among the many materials now enabling medical engineers to design innovative, and increasingly biocompatible, replacements for damaged human tissues

by Robert A. Fuller and Jonathan J. Rosen

Given the task of replacing a defective body part, many physicians would pass up an artificial substitute in favor of a tissue-matched transplant from a human donor. Natural tissues and organs, after all, contain exactly the mixture of materials needed to fulfill the body's functions. Nevertheless, transplantation often is not an available option.

In part to sidestep the need for living grafts, a number of investigators are developing artificial tissues and organs, an endeavor that has been particularly productive in the past few decades. Among the factors accounting for this recent success is an explosion of research, begun in the early 1950's, into biomaterials: nondrug substances suitable for inclusion in systems that augment or replace the functions of bodily tissues or organs.

Today biomaterials lend themselves to an array of applications, from intraocular-lens replacements to artificial hearts. Because progress has been so great, we cannot begin to describe all, or even most, of the highly promising systems and materials on the market or under study. We shall therefore limit ourselves to several examples of medical systems that have benefited from the development of new materials or from the novel application of materials that were originally developed for nonmedical purposes.

Before addressing specific materials applications we should point out that investigators who develop biomaterials face a unique challenge. To be acceptable as a biomaterial a substance must certainly pass mechanical muster, but it also has to be biocompatible: it must interact with the host in a nontoxic, controlled and predictable way.

At one time biomedical scientists focused on materials that reacted little with tissue and triggered the least reaction. Such inertness is still an important objective for many purposes, but nothing is totally inert in the body. Moreover, workers now recognize that not all interactions between foreign materials and the body are bad. Certainly materials that result in inflammation or a rejection reaction are undesirable. On the other hand, several materials that are highly interactive are proving to be increasingly valuable. Some implant materials, for instance, form chemical bonds with nearby tissue, stabilizing the implant. Certain other materials are gradually resorbed (broken down and absorbed) by the body when they are no longer needed for their initial purpose.

One endeavor that benefits markedly from progress in materials science is the effort to develop replacement parts for the cardiovascular system. Some of the materials contributing to advances in this area are quite inert and some are interactive, but all have to meet particularly demanding mechanical and biocompatibility requirements. The normal heart beats approximately 40 million times each year. Artificial parts designed to pump the blood, such as sacs in cardiac-assist devices, must therefore be made of materials that are able to remain flexible without tearing or becoming misshapen.

Materials that come in contact with flowing blood have additional requirements: they must not damage blood cells or encourage the formation of destructive blood clots. When flowing blood meets a foreign material, some degree of protein and blood-cell deposition on the material is practically inevitable. If this process continues, the resulting clot, or thrombus, can interfere with the intended function of the device. Such clots can also block blood vessels at implant sites or break off completely, leading to vessel blockage or tissue damage at distant sites, such as the heart or brain.

No single synthetic material has yet satisfied all the mechanical and blood-compatibility requirements of the cardiovascular system, but several substances have proved to be usable. Silicones that are chemically modified to resist adhesion by the proteins and fats in plasma have been incorporated in treatment systems, although their strength and durability are limited. Polyurethane-based polymers possess better mechanical characteristics and some provide extraordinary flexibility and durability. Several of the polyurethanes are also quite blood-compatible, such as the polyether-based Biomer, developed for medical applications by Ethicon in Somerville, N.J. A pure, glassy carbon material originally developed to encapsulate fuel for nuclear reactors—pyrolytic carbon—is an alternative high-strength, blood-compatible material for some applications that do not require flexibility. In addition to being quite inert in the body, pyrolytic carbon is unusually resistant to wear and fatigue.

In the past 30 years heart-valve replacements, which have undergone

INTERFACE between a rat tibial bone (*left*) and the surface of an implant made of Bioglass (*right*) is seamless because the bone binds to the implant. (The dark area at the far left is bone marrow.) After implantation the Bioglass develops surface layers rich in calcium phosphate (*adjoining the bone*) and in silica (*far right*). Calcium phosphate in the bone binds to the calcium phosphate in the implant, and collagen produced by osteoblasts (bone cells) in the area is also incorporated into the surface of the glass. Binding between bone and an implant stabilizes the implant and prevents loosening. At one time biomedical engineers primarily sought inert materials for implantation, but "bioactive," or interactive, materials are currently attracting increasing interest for certain purposes. Additional bone-binding materials include calcium phosphate ceramics and glass-ceramics.

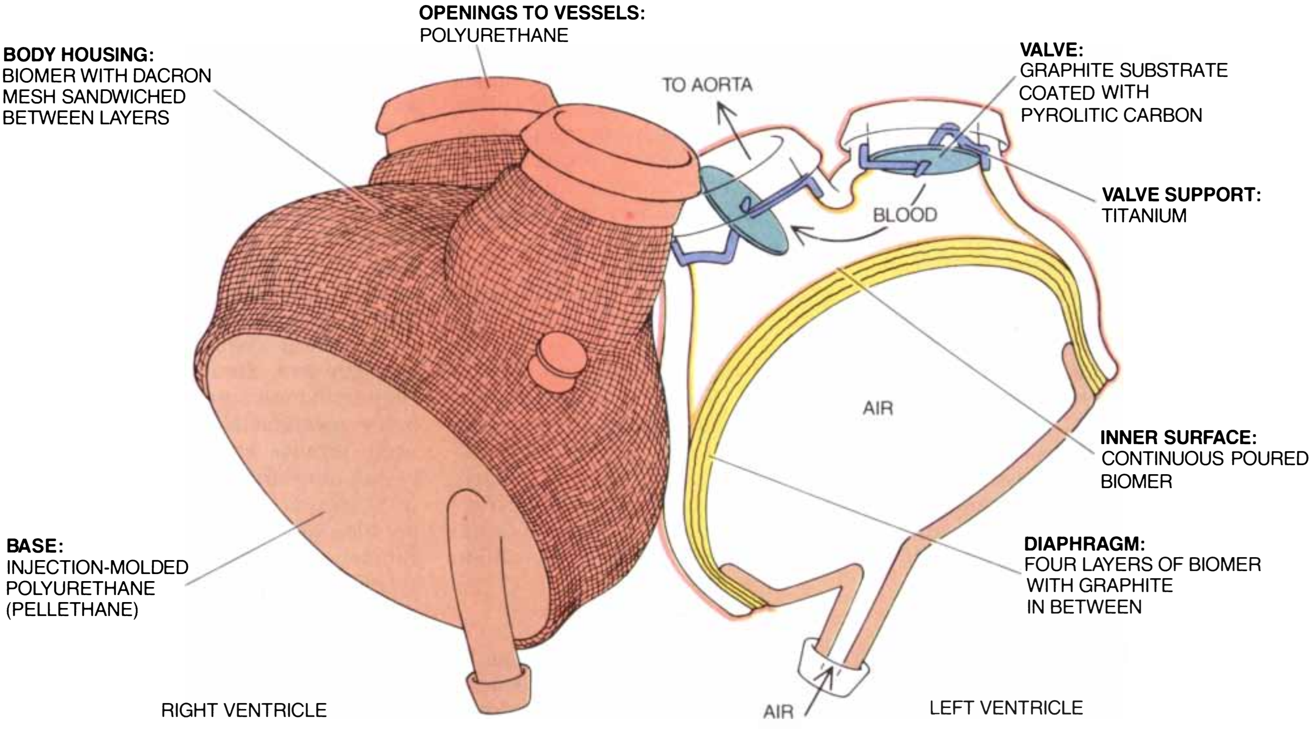
many design changes, have tested the biocompatibility and the durability of many new materials. The earliest mechanical valves were made from stainless steel and silicone rubber; these substances were reasonably durable, but anticoagulant treatment was necessary to prevent blood-clot formation. In the late 1960's workers introduced a second approach: chemically modified animal tissues. Such valves required little or no anticoagulant administration but generally were less durable. Several recent valves have been made with pyrolytic carbon in an effort to provide both mechanical strength and superior blood-compatibility. The valves in the Jarvik-7 artificial heart include this carbon. Even the most advanced heart-valve designs are not completely free of problems, and the search for ideal designs and materials continues.

Left-ventricular-assist devices for the heart, many of which are still under development, also feature an array of new materials. These temporary pumps relieve the strain on a failing heart by helping to maintain normal blood flow. Of particular interest in these devices are the materials for the sac that collects blood from the heart and pumps it to the aorta. Some investigators design sacs to have particularly smooth blood-contacting surfaces, perhaps coating them with Biomer or with a gelatinous material developed at the Cleveland Clinic Foundation.

Some workers are also testing sacs made with textured material, such as polyurethane that has fibrils incorporated at the surface. A textured blood-contacting surface aims to "fool" the blood into producing a pseudointima: a stable, biological approximation of a natural lining. When blood comes into contact with a flocked surface, proteins in the blood adhere to the material, as do platelets and the protein fibrin, which traps blood cells. Next, fibroblasts nestle into the developing lining and produce collagen, a fibrous protein found in connective tissue throughout the body, including the tissue of blood vessels, bone, tendons and ligaments. Eventually the deposition of collagen results in a smooth and presumably stable biological surface. In the past decade investigators have also developed a similar approach to constructing artificial blood vessels. For instance, vessels are made of polytetrafluoroethylene (PTFE), a polymer that can be stretched to increase porosity. Pores encourage plasma proteins to attach to the surface, leading to the production of a pseudointima.

Clearly various systems facilitate blood circulation. What about the blood itself? To date, synthetic blood substitutes can carry out only part of the blood's many vital functions. Various essentially inert polymers, such as the water-soluble substance polyvinylpyrrolidone, can restore blood volume, thereby preventing or treating shock, the circulatory failure that follows the loss of fluid from blood vessels. Another class of polymers, perfluorocarbons (which have a carbon atom for every fluorine atom), can directly transport oxygen. These polymers can therefore potentially treat anemia or other conditions marked by inadequate blood-oxygen levels, such as tissue ischemia: a deficiency of blood in a tissue owing to obstruction of a blood vessel. Derivatives of hemoglobin, the molecule in red blood cells that normally transports oxygen, can also perform this task.

The earliest perfluorocarbon blood substitute, Fluosol, made of perfluorodecalin and perfluorotripropylamine, is perhaps the best-known, but it has been disappointing for treating ischemia. Several newer perfluorocarbon compounds have a larger oxygen-carrying capacity (in many cases greater than that of hemoglobin itself), and some of these materials may eventual-



JARVIK-7 ARTIFICIAL HEART has benefited from advances in polymer development. The cutaway shows the left ventricle during systole. An inflow of air has expanded the diaphragm, forcing blood out of the overlying cavity and into the aorta. The polyurethane Biomer, which is inert, flexible and durable, is a major component of the housing and the diaphragm. Liquid Biomer is also poured into the cavity to form a smooth, uninterrupted blood-contacting surface. Other polyurethanes form the base and the openings at the top. Dacron, a polyester, gives rigidity to the housing. Of the nonpolymers, graphite lubricates the diaphragm and gives shape to the valve disks; pyrolytic carbon makes the disks strong and glassy and titanium is a durable, noncorrosive frame for them.

ly find application in new medical treatments.

Perfluorocarbons might, for example, serve one day as a component in an emergency treatment for ischemic stroke, an episode of interrupted blood flow to the brain. When a human being or an animal suffers a stroke, brain cells can die, resulting in permanent damage. If, on the other hand, some fluid can supply nutrients and oxygen to the brain until the blood once again performs this task, the brain's normal function may be protected.

Jewell L. Osterholm and his colleagues at the Jefferson Medical College in Philadelphia have developed such a fluid, successfully testing it in laboratory animals that suffered severe ischemic strokes. The test fluid contained nutrients and the perfluorocarbon perfluorobutyltetrahydrofurane, to provide oxygen. The workers bathed the brain with the material by delivering it through a catheter in the skull. Remarkably, animals that had flat electroencephalogram readings, the accepted criterion for brain death, successfully revived and subsequently showed apparently normal electroencephalogram patterns. If similar treatment is successful in human beings, it would be the first significant approach to reducing the effects of a leading cause of disability and death.

Whereas most materials for cardiovascular systems have to be elastic and blood-compatible, materials for osseous, or bone, implants must be rigid and stress-resistant. In addition osseous implants should ideally reside in the bone without interfering with bone remineralization, the natural process by which the body replenishes resorbed bone. Indeed, for some procedures, such as long-bone or tooth repair, the ideal implant might actually facilitate the regeneration of a damaged bone, dissolving as new bone is produced to take its place.

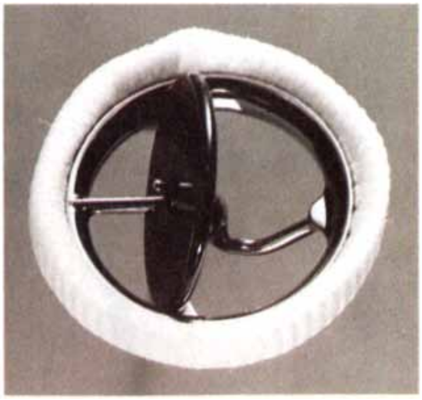
Metallic prostheses have long been the mainstay of both orthopedics and dentistry. Even today many dental, joint and long-bone implants contain the metal titanium or alloys made of chromium and cobalt. In fact, one of the newest types of permanent tooth implants is made with titanium posts that are implanted into the underlying bone; the replacement teeth are then attached to the posts.

Metallic implants are strong and do not fracture, but they do have potential drawbacks. While one risk—corrosion—is not very common today, metallic implants or the cements that fix them in place (often the polymer polymethyl methacrylate, PMMA) do sometimes cause localized inflammatory reactions at the implant site. Moreover, at least in theory, metal ions can leave the implant and find their way into the bloodstream, causing adverse reactions.

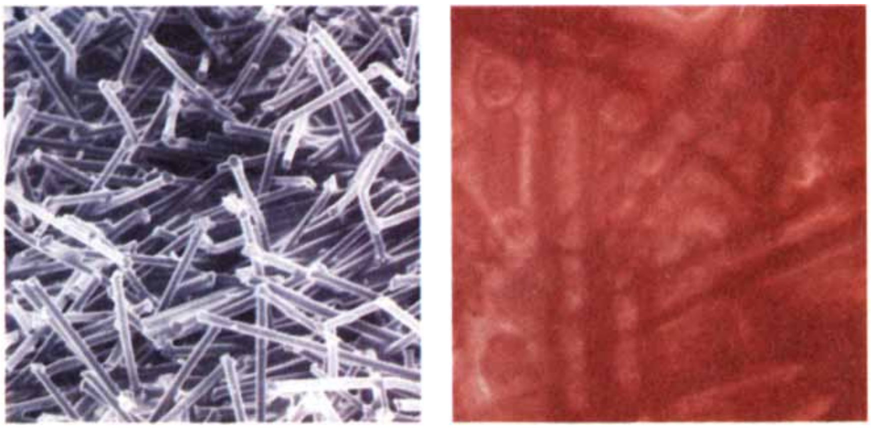
What is more important is that metallic implants are mechanically and compositionally quite different from a host's tissues. Because metals are stronger than natural bone, they tend to bear directly the brunt of any loads placed on the bone. Stress on the bone normally stimulates bone to grow; therefore stress "shielding" by the implant can lead to bone resorption and in turn to loosening of the implant. Indeed, few load-bearing metallic implants last for more than 20 years, making them less than ideal for young people. Loosening can be alleviated by giving the implants a porous metal surface that allows bone to grow into and attach to the prosthesis. Unfortunately this bonding does not always prevent bone loss that results from resorption.

In the hope of increasing the life of implants, several investigators have in the past 15 years experimented with bone replacements made of inert nonmetallic materials. Some workers, for instance, are studying polymers that are reinforced with strong carbon fibers; these implants seem to transfer stress from the implant to the nearby bone, thereby avoiding excessive bone loss. Various laboratories have also developed "bioactive" (interactive) ceramics, glasses and glass-ceramics that form chemical bonds at their surfaces with adjacent bone and are believed to encourage new bone to form.

The surface-active materials called Bioglasses were the first substances shown to be capable of forming chemical bonds with bone. In Bioglasses, which were developed by Larry L. Hench of the University of Florida at Gainesville, some of the silica of conventional glasses is replaced by calcium, phosphorus and sodium, all of which are components of natural bone. Calcium phosphate ceramics, another category of surface-active materials, have also been found to bind with bone and are widely used to build up or repair the jawbone. Calcium phosphate ceramics may eventually prove to be the most biocompatible synthetic systems for hard-tissue replacement. They reportedly elicit no inflammatory or rejection responses by the body, bond strongly to bone by apparently normal bone-cementing



VALVE incorporated in the Jarvik-7 artificial heart, the Medtronic Hall valve, is smooth enough to discourage the development of blood clots on its surface. The white sheath is a sewing ring for attaching the valve to a natural heart; it is not required in the Jarvik-7 heart and is omitted.



TEXTURED MATERIAL, such as a polyurethane whose surface is flocked with fibrils (*left*), is being tested as a blood-contacting surface in some ventricular-assist devices. In contrast to smooth surfaces, textured ones are designed to trap and anchor components from the flowing blood. After the material comes in contact with the blood (*right*) the fibrils trap such substances as platelets, proteins, red blood cells (*disks*) and white blood cells. The resulting matrix of cells and protein is then transformed into a smooth, thin layer. Eventually the protein collagen covers this layer, stabilizing it. When all goes well, the result is a blood-contacting surface much like the lining of a natural blood vessel.

CARBON STRAND containing 10,000 fibers individually coated with polylactic acid forms a strong, elastic, manageable implant for the repair of tendons and ligaments. The composite material, developed by Harold Alexander and J. Russell Parsons of the University of Medicine and Dentistry of New Jersey at Newark, is woven in and around a damaged tissue. Within two weeks the body absorbs the polylactic acid, replacing it with cells that begin to produce new connective tissue. Within nine months to a year new tissue surrounds the implanted fibers. In the micrograph a cross section of a ligament is seen, enlarged 400 diameters, 11 months after carbon fibers (*tubular shapes*) were implanted.

mechanisms and do not interfere with the natural deposition of mineral in nearby bone.

Many investigators expect calcium phosphate ceramics, Bioglasses and glass-ceramics (glasses made mechanically stronger by the growth of crystals in them) to have a place in both dental and orthopedic repair in the future. Nonmetals can, however, fracture under loads. Hence in the years to come many load-bearing implants may have metallic substrates mixed with (or coated by) ceramic, glass or glass-ceramic bioactive materials. These implants could be held in place not by cement but by materials that encourage the growth of a natural bone-to-bone seal. Several laboratories are attempting to develop such combinations.

Some new materials appear to be particularly promising for dentistry, specifically for cosmetic tooth restorations. These materials include porcelain- and polymer-based composites that are highly resistant to fracture and loosening. The new systems, which can be colored to match the patient's teeth and are stain-resistant, are suitable for filling cavities, repairing crowns and covering surface imperfections.

Nonosseous parts of the musculoskeletal system are also benefiting from advances in biomaterials technology. In particular, new biomaterials are improving the repair of ligaments and tendons: the tough, elastic fibers that respectively bind bone to bone and muscle to bone or to muscle. Several materials under study or in use were originally developed for nonmedical purposes, including the rubberlike polymer Kevlar (coated with smooth silicone to improve biocompatibility), Dacron polyester fiber, PTFE polymers and pyrolyzed carbon fibers made by heating rayon fibers until only their carbon chains are left. Alone, each material is usable but not ideal for tendon or ligament repair. For instance, Dacron is not as strong as Kevlar but does encourage new-tissue growth; the carbon fibers are strong but can be brittle.

One material that may overcome the drawback of implanting carbon fibers is a composite developed by J. Russell Parsons, Harold Alexander and their colleagues at the University of Medicine and Dentistry of New Jersey at Newark. These workers implant pyrolyzed-carbon fibers that are individually coated with polylactic acid, a flexible but not particularly strong polymer of lactic acid. (Lactic acid occurs naturally in the body.) The composite is strong yet easy for a surgeon to handle.

Within about two weeks after a surgeon weaves an implant containing 10,000 fine fibers into damaged tendons or ligaments, the body absorbs the polylactic acid and replaces it with cells that produce collagen. In time new connective tissue grows around the carbon scaffolding. Recent investigations suggest that workers might be able to produce a form of polylactic acid that is strong and stable enough to substitute directly for carbon and to handle the stresses placed on tendons and ligaments during the healing period. Once the polymer is no longer needed it would then be resorbed, leaving behind no foreign material that could induce inflammation or other adverse reactions.

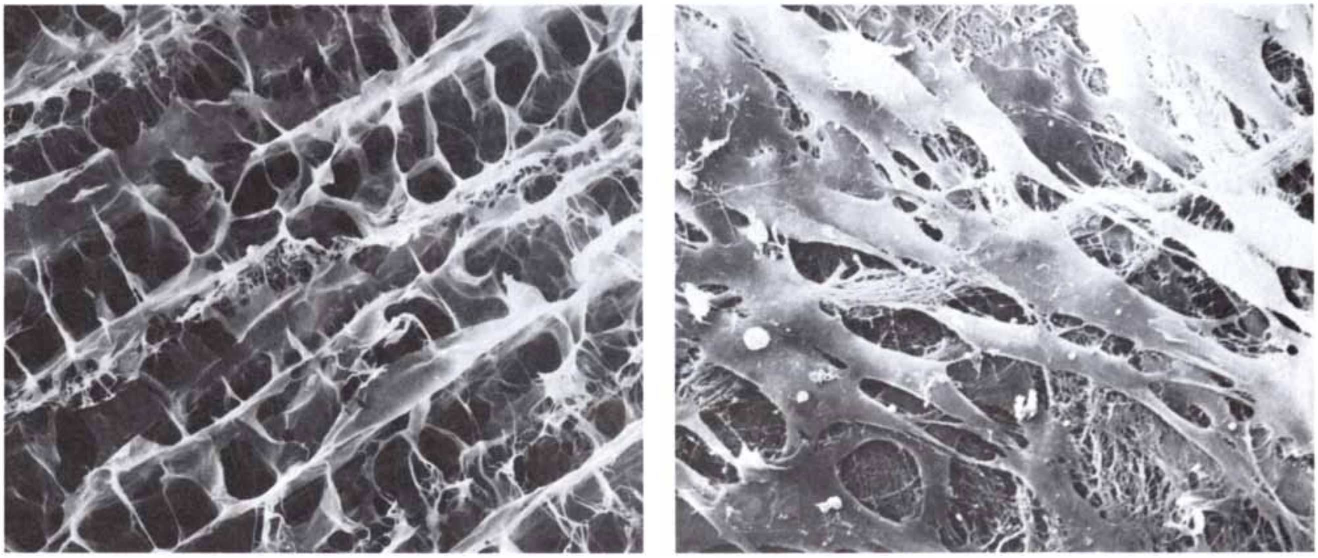
The human skin is another tissue for which many investigators have long sought synthetic replacements. Such replacements become particularly important when people suffer serious burns over large parts of their body. The skin, which helps the body to resist infection and retain water and electrolytes, has two major layers. The bottom layer, the dermis, includes dense connective tissue as well as hair follicles, nerves and blood vessels. The top layer, the epidermis, has several subdivisions and components, including the water-resistant protein keratin.

Workers have experimented for many years with polymeric substitutes for normal skin. Until recently these substitutes could not prevent the onset of infection and were likely to trigger a rejection reaction. Within the past few years, however, several laboratories have produced remarkably successful materials for skin replacement, many of which are now in advanced stages of testing.

At the Massachusetts Institute of Technology, Ioannis V. Yannas and his colleagues produce a biodegradable skin substitute, called Stage 1 skin, that appears to stimulate new skin growth. The structural component of the material is a porous polymer derived from bovine collagen fibers. The workers combine this with chondroitan-6-sulfate, a polysaccharide from shark cartilage, to lower the rate at which the host's body degrades the collagen. Then they cover the material with silicone rubber to prevent infection and fluid loss.

After physicians suture the new "skin" in place, fibroblasts from underlying connective tissue migrate to it. The cells produce a "neodermis." After about three weeks, when the collagen polymer is largely degraded, the workers remove the silicone and transplant small pieces of epidermis from the patient's body over the neodermis; a new epidermis forms within several days. As is true for other skin replacements, the new skin functions like natural skin but lacks hair follicles and sweat glands. Frederick H. Silver of the University of Medicine and Dentistry of New Jersey at Piscataway, who has also produced a bovine collagen matrix, suggests that such matrixes might one day be coated with anticancer drugs and then applied to parts of the body where malignant tumors are removed, thereby potentially re-

STAGE 1 SKIN (*left*), developed by Ioannis V. Yannas of the Massachusetts Institute of Technology, combines a polymer made of bovine collagen with a polysaccharide, which lowers the rate at which the recipient's body degrades the collagen. Once the material is sutured in place, cells from the recipient migrate to it and produce a new dermis; then physicians transplant epidermal cells from the recipient onto the surface, allowing a new epidermis to grow. In 1981 John F. Burke of the Massachusetts General Hospital used Stage 1 skin on the abdomen of Mark Walsh, an electrician who suffered third-degree burns over most of his body. The skin that grew in (*right*) appears normal except that it lacks hair and sweat glands. A Stage 2 skin, which is seeded with epidermal cells before implantation to hasten healing, is now under study.



ANOTHER COLLAGEN MATRIX (*left*) designed to encourage the growth of new skin has been developed at the University of Medicine and Dentistry of New Jersey at Piscataway. The collagen is freeze-dried by a process that controls the porosity of the matrix, which becomes transparent and spongelike when it is mixed with water. After the material is placed on a wound (*right*) its cavities collect normal skin cells (*long irregular bands*); these cells accumulate around the matrix and eventually take its place.

ducing the chemotherapy dosages patients require.

Several other investigators, such as Howard Green and his colleagues at the Harvard Medical School, are exploring another way to replace skin: tissue culturing. Green's group begins with a skin sample from the recipient as small as a square centimeter. Then they culture epidermal cells from the sample in a mixture of inactivated fetal fibroblasts, epidermal growth factor and an agent that increases the metabolic activity of the skin cells. The fibroblasts provide a matrix for the multiplying skin cells, which form a sheet of new, layered epidermis containing keratin. With material produced in this manner, Green and his colleagues were able in 1983 to save the lives of two brothers, six and seven years old, who suffered burns over 97 percent of their bodies and had more than 80 percent of their natural skin completely destroyed. Both brothers have functioning, smooth skin today.

The techniques for producing skin replacements may lead the way to methods for synthesizing other tissues. Eugene Bell and his colleagues at M.I.T. have, for example, produced not only skin but also a synthetic thyroid gland that in rats apparently produces the hormone thyroglobulin. To produce their skin equivalent these investigators mix fibroblasts from the recipient with a solution containing rat collagen, rat serum and a tissue-culture medium. In time the collagen traps the cells and causes the matrix to condense into a dermal equivalent. Once the dermis is produced the workers scatter epidermal cells onto it, thereby producing a single epidermal sheet within a few days. To make thyroid tissue the group puts thyroid cells rather than fibroblasts into the culture solution.

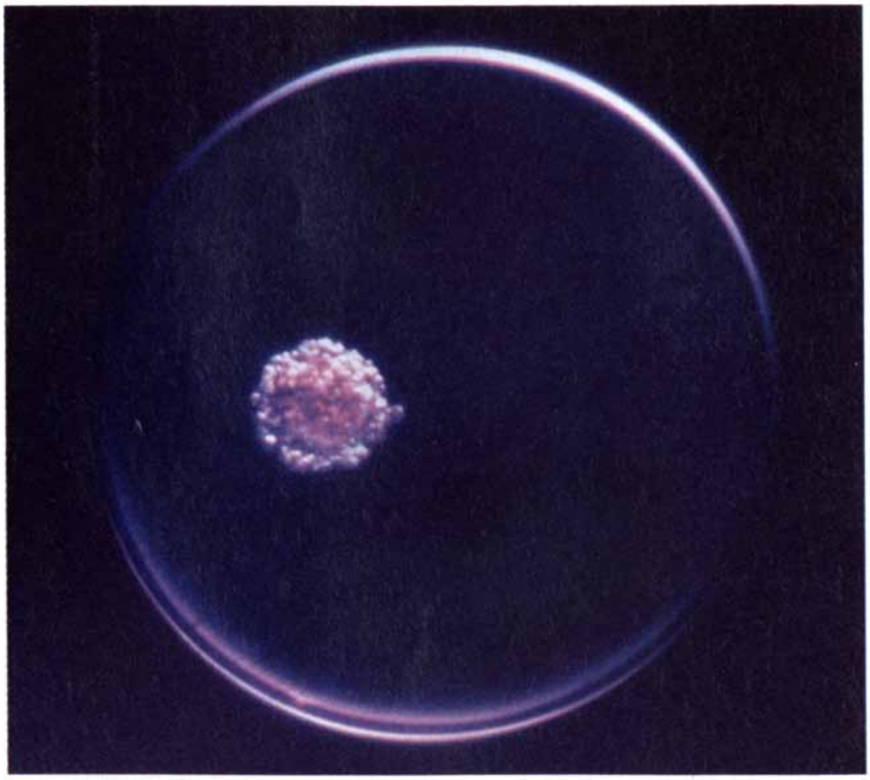
Bell also hopes to synthesize a form of pancreatic tissue by culturing pancreatic beta cells, the cells that produce insulin. In a much more advanced stage of development, however, is an artificial endocrine pancreas being perfected by Anthony M. F. Sun of the University of Toronto.

A successful pancreatic replacement could help the thousands of people with diabetes whose beta cells have been destroyed. These people must now attempt to normalize blood-glucose levels (and other metabolic abnormalities) by taking one or more daily insulin injections. In Sun's system individual islets of Langerhans (the pancreatic cell clusters that incorporate beta cells) are encapsulated by a composite material consisting of an amino acid polymer and sodium alginate, a polysaccharide polymer derived from seaweed.

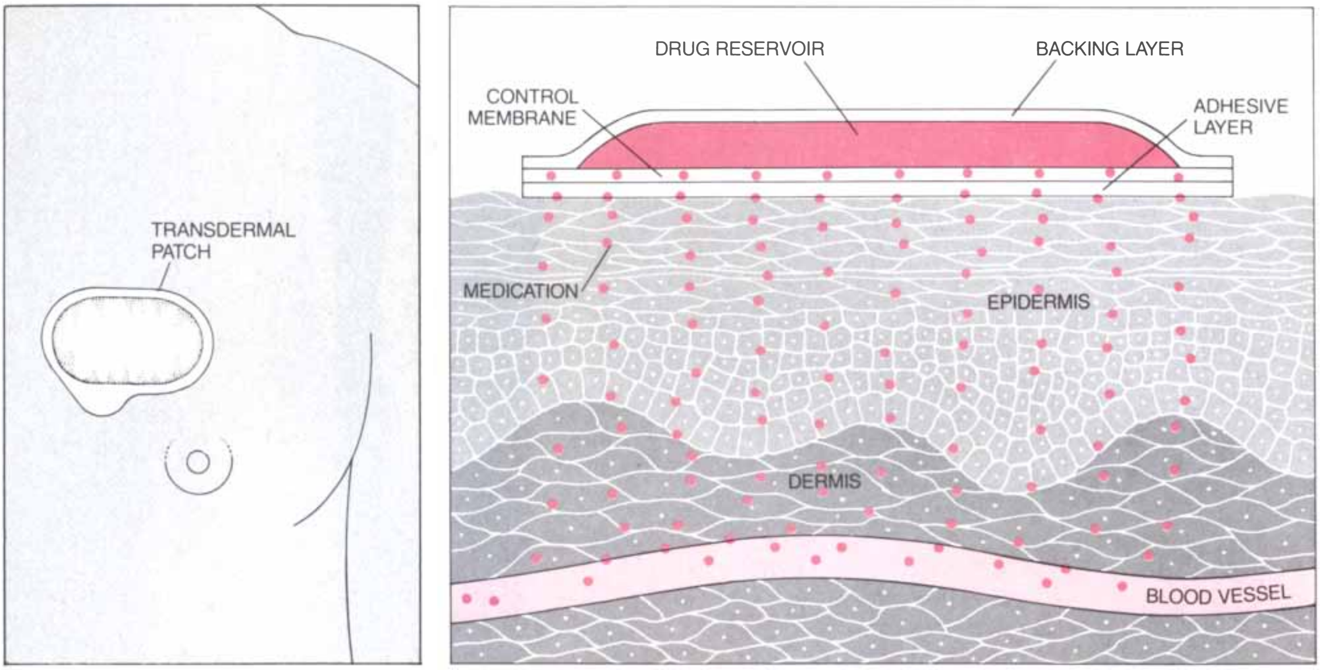
The amino acid polymer provides strength and the sodium alginate provides structure; the two together form a membrane that "hides" the foreign islets from the host's immune system (because the molecules of the immune system are too large to pass through the membrane), thereby forestalling rejection. Moreover, the membrane is strong enough to survive implantation by injection but is porous enough to allow insulin to leave, and glucose to enter, the capsule. The glucose triggers the release of insulin, much as elevated glucose levels in the body stimulate the pancreas to secrete insulin in people who do not have diabetes. A single injection of the microscopic spheres, which are each from 300 to 600 micrometers in diameter, has controlled diabetic symptoms in laboratory animals for more than a year. Clinical trials are expected to begin within the next two or three years.

A final example of how progress in materials science has advanced the development of implantable treatment systems is the evolution of the intraocular-lens implant. In the 1940's a British ophthalmologist noted that fragments of plastic airplane cockpit covers made of polymethyl methacrylate caused little or no negative reaction when they became traumatically embedded in a pilot's eyes. Within a few years this observation led to the surgical insertion of the first PMMA lens implants in patients who had been operated on for severe cataracts. Lens implants continued to be made of the same PMMA for about 40 years. The material was then modified in the early 1980's to prevent lenses from being discolored by ultraviolet light.

More recently investigators have developed foldable lenses made of silicone rubber or of hydrogel, a viscous, jellylike polymer. These can be implanted in the eye through a much smaller incision than is required for PMMA lenses. At least one laboratory is reportedly taking these improvements one step further, developing an injectable material that would be inserted as a liquid and would then polymerize in place to form a new lens.



MICROCAPSULE surrounding a pancreatic islet of Langerhans is made of two polymers: a polysaccharide that provides structure and a protein that provides strength. Pancreatic islets normally incorporate the body's insulin-producing cells, but in many people with diabetes these cells are destroyed or impaired. Transplantation of pancreatic tissue, a logical treatment for diabetes, has largely been ineffective because the host's immune system recognizes that the implanted islets are foreign and produces antibodies to attack them. In diabetic animals the polymer capsule has been shown to be a barrier to antibodies, which are large molecules. The capsule is nonetheless porous enough to allow insulin from the islets to leave the capsule and fulfill the hormone's normal functions. Encapsulated islets have controlled diabetes in test animals, but clinical trials have not yet begun.



TRANSDERMAL PATCH (*left*) developed by the Alza Corporation stores nitroglycerin (for treating angina) in a reservoir. It is made of several polymers, each designed to perform precise functions. In a typical reservoir system (*right*) polymers form the thin backing (which prevents the patch from drying out), the drug reservoir, the membrane that controls the rate of medication release and the adhesive layer. To reach the bloodstream from the transdermal patch medication (*dots*) in the reservoir passes through pores in the control membrane and adhesive layer and then diffuses through the epidermis to blood vessels in the dermis below.

Implantable systems are probably among the most exciting applications of biomaterials, but systems that otherwise aid in the delivery of medical treatment are also important. Casts made of polymers, for instance, are now challenging plaster-of-Paris casts as the choice for external fixation of bones. Within the past several years workers have developed polyurethane materials that have the right combination of properties: strength, low weight and resistance to wetting and breakdown. Such casts allow patients to move with greater freedom and to bathe more easily.

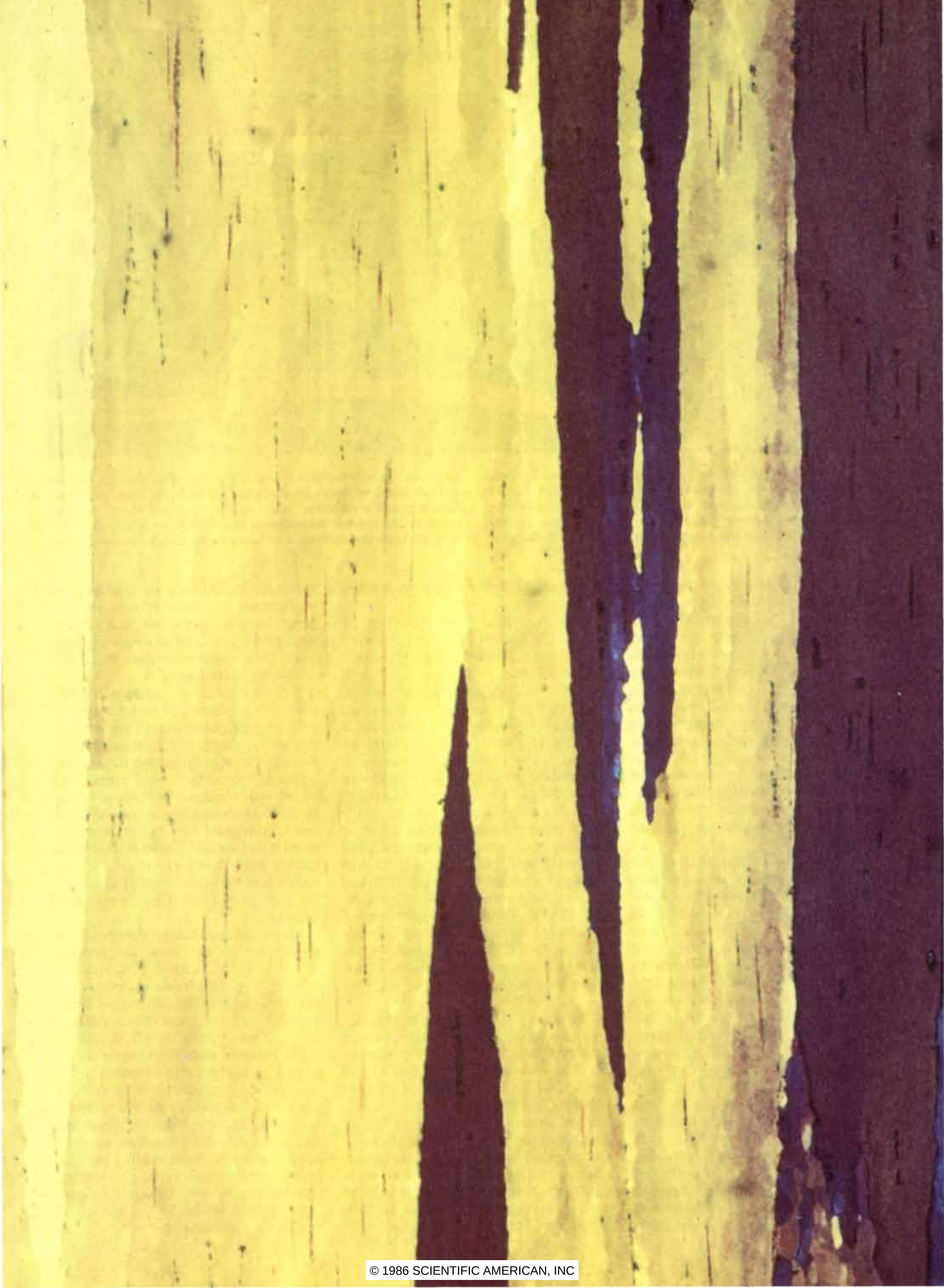
Another aid to wound healing, the suture, is perhaps one of mankind's earliest attempts to transform a natural substance into a biomaterial. In various forms, catgut sutures have closed wounds in injured tissues since as early as A.D. 175. Synthetic absorbable sutures made of glycolic acid polymers or copolymers have virtually replaced catgut in recent years. These polymers elicit minimal tissue reaction and can be produced in very fine sizes (as small as one-tenth the diameter of human hair), enabling physicians to perform microsurgery. Other polymers, notably polypropylene, have by and large replaced earlier suture materials for cardiovascular surgery because they are nonabsorbable, smooth and made of single filaments. Because these filaments do not shred, they enable physicians to form uninterrupted stitches at a time when speed is important.

Transdermal skin patches that adhere to the skin and deliver controlled doses of medication are having a profound effect in several areas of drug therapy. Patches now deliver medication for motion sickness, angina and hypertension and are being considered for the delivery of antihistamines, insulin, contraceptives and even certain anticancer drugs. These apparently simple systems can contain as many as 10 distinct polymers, each of which has a different purpose. Adhesion to the skin, moisture retention, control of the rate of drug delivery and storage of a drug in a reservoir are each achieved by materials with specialized properties. For the future, many groups are developing transdermal drug-delivery systems that will simultaneously release two or more medications at different delivery rates.

The future is sure to see increasingly complex uses of composites and bioactive and biodegradable materials. The successful application of the new materials will depend in part on progress in discovering the properties of those materials, particularly the properties of the surface. How are the molecules at the surface oriented, what is their composition and what kinds of chemical interactions occur between the material's surface and living tissue? Recent advances in spectroscopic techniques are enabling investigators to study minute interactions between materials and tissues, such as the behavior of single proteins when they come in contact with various material surfaces.

In a parallel sense, progress in materials development will be informed by advances in physiology, immunology and cell biology, which have recently provided new insights into the mechanisms involved in wound repair and blood coagulation. An understanding of these processes and other tissue actions, combined with a better understanding of surface-tissue interactions, should help investigators to develop increasingly tissue-compatible materials and thus increasingly successful treatments.

Materials suitable for medical systems have always been the product of an interdisciplinary collaboration among investigators in materials science, bioengineering, clinical medicine and the various basic biological sciences. This continuing effort has already resulted not only in systems designed to correct life-threatening organ failure but also in systems that cope with less serious disorders. Work is also under way to develop implants and other devices that might actually prevent chronic and disabling medical problems. We expect that new biomaterials systems will continue to promote advances in every aspect of health-care technology.



The Science of Materials

The extraordinary diversity of today's advanced materials is based on better knowledge of how to attain novel structures displaying new properties that lead to improved performance

by Gerald L. Liedl

Sometime in the eighth millennium B.C. human beings found that a piece of clay shaped into a pot could be hardened by fire and that the pot, once fired, would retain liquid and resist deformation even when it was set in hot coals. A soft, malleable material had been converted into a hard, stonelike one. That first intentional transformation of an inorganic natural material into a new material displaying novel properties was the beginning of materials technology or engineering.

Some 7,000 years later Greek philosophers speculated that all matter consists of minute, indivisible particles of the same basic substance. That early attempt to understand the nature of material things can be taken as the beginning of materials science.

Until very recently the practitioners of materials engineering and materials science remained separated by a wide gulf. Craftsmanship and technology flourished. The selection, modification and processing of materials came to be fundamental elements of human cultures. Yet the science of materials—an attempt to understand their fundamental nature and why particular manipulations of them have particular effects—was slow to develop beyond the level of speculation. It was not until the 19th century that chemistry and to a lesser extent physics began to support the largely empirical efforts of artisans and engineers with applicable theories and novel analytical tools. Within the past half century the collaboration has thrived. The advent of powerful new theories and instrumentation has made investigative science an essential driving force for advances in engineering.

A stick of wood, a stone and a bed of clay are naturally occurring materials. They are also technological materials, because they can become a club, an ax and a pottery bowl. A technological material is a natural one that is put to use by human beings or is processed and thereby given new properties that transform it into a useful object. A stick is converted into a club simply by being seen as potentially useful and being picked up; a stone is shaped into an ax. The clay, however, requires both shaping and conversion by heat if it is to become an effective pot. The choice of the best clay available, the application of the correct amount of heat for the right time and the proper cooling and surface treatment of the fired pot all contribute to the making of an effective utensil.

The early artisans developed their knowledge of materials—first ceramics and then bronze and iron—and of techniques for manipulating them empirically. Archaeologists unearth their artifacts; materials scientists can analyze the artifacts and deduce something about the techniques whereby they were produced, but there is no way to gauge how well artisans understood the nature of their materials until after the advent of printing. Such 16th-century works as the *De la Pirotechnia* of Vannoccio Biringuccio and the *De Re Metallica* of Georgius Agricola provide the first insights into details of the era's materials technology and the level of artisans' understanding of their materials.

They knew, for example, how to combine charcoal with an ore in smelting in order to reduce the ore to its metallic content, how to mix two metals to form an alloy more workable and ultimately stronger than either metal alone, how to harden a metal by quenching or hammering. Such working knowledge of materials and processes, although impressive, had clearly come from practical experience. Little if anything had been contributed by scholars. Alchemists did not talk to blacksmiths.

This lack of intellectual input persisted even through the scientific revolution of the 17th and 18th centuries, the Industrial Revolution and the first burgeoning of industry in the early 19th century. Technological materials were simply too complicated and too unpredictable for investigators and for the instruments at their disposal. Artisans knew that each material had specific qualities and knew how to work the material, exploiting its qualities to make marketable goods. It was explanation that was lacking, and without explanation there could be no accurate prediction of how a change in processing might improve the performance of a material.

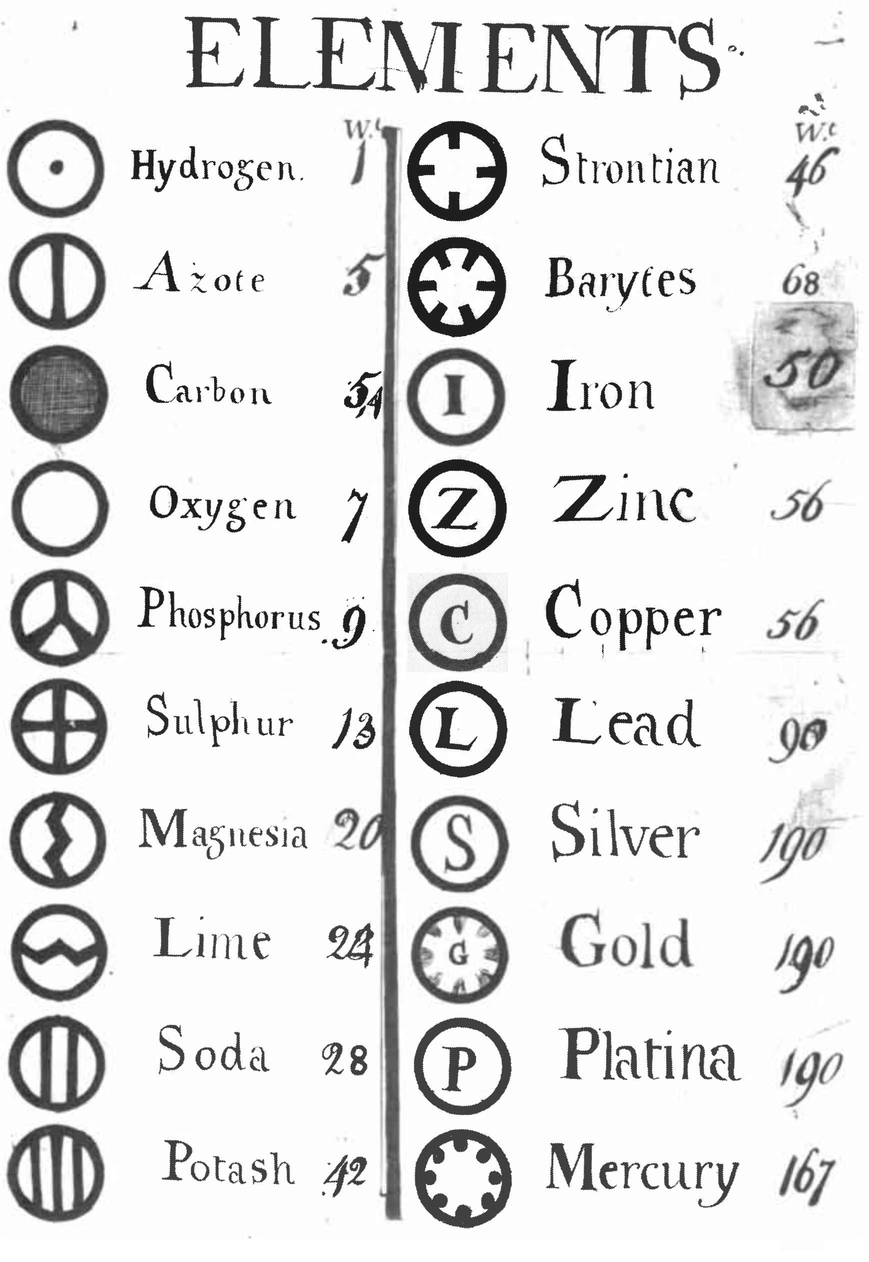
The first spin-offs from real understanding of materials came later in the 19th century. It began with chemistry. Chemical theory proved to be helpful as a guide to the more efficient processing of materials that had been known for centuries. For example, knowledge of oxidation was applied to steelmaking: controlled amounts of oxygen, supplied under pressure to a molten metal, combine with impurities to form oxides that can be removed from the melt, as in the Besse-

MICROSTRUCTURE of an aluminum-lithium alloy is revealed in a photomicrograph, made under polarized light, of a cross section of the sample. The micrograph, in which the sample is enlarged some 265 diameters, was made at Alcoa Laboratories. Differently colored regions represent differently oriented crystal grains of the alloy, which is lighter and stiffer than unalloyed aluminum. Better control of microstructure has greatly increased the ability of materials scientists to develop materials having novel properties.

mer process. Chemical analysis came to be an essential tool for choosing the right raw material and for the control of processing. Assaying procedures monitored the fate of particular elements, such as carbon, in the course of steelmaking.

A new tool was brought to bear in 1866, when Henry Clifton Sorby, an English geologist and pioneer in microscopy, first applied the light microscope to the study of steel. He observed that the texture of a fractured surface was actually crystalline in nature and that it differed depending on the precise composition of the steel and its thermal treatment. This seminal observation of changes in the internal structure of a metal, coupled with the new knowledge about composition from analytical chemistry, signaled a profound change in the degree to which the fundamental nature of materials could be understood.

By the last quarter of the 19th century chemistry and physics had essential process-control roles in many established materials industries. In 1886 physical science laid the groundwork for a brand-new materials industry: the American chemist Charles Martin Hall learned how to produce metallic aluminum economically by passing an electric current through fused (molten) cryolite, a sodium aluminum fluoride. Within the next few decades significant new processes were developed for the production of high-carbon, silicon and stainless steels.



ATOMIC THEORY was advanced by John Dalton at the beginning of the 19th century. In a chart displayed during lectures he showed symbols for what he took to be the irreducible "elements or atoms," with atomic weights based on a weight of 1 for hydrogen.

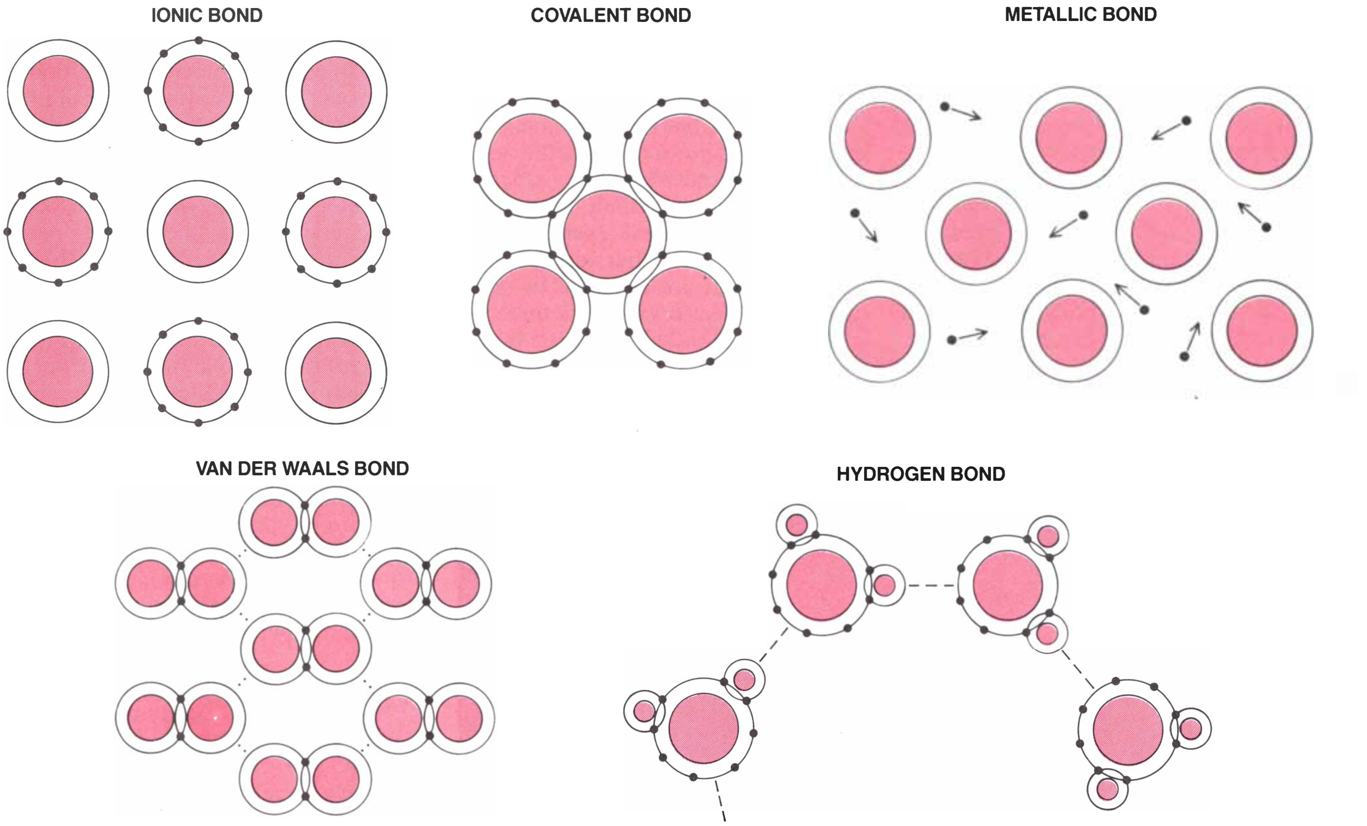
It has been in the 20th century, and particularly in the past 40 years, that chemists and physicists have been able to achieve the fundamental insights that now drive advances in the development of new materials and new processing technology. The deeper theoretical understanding of materials, coupled with powerful analytical tools for studying materials, has led to close cooperation between materials scientists and engineers.

The key contribution of science was the coupling of a material's external properties to its internal structure. Materials were discovered to possess an inner architecture—a hierarchy of successive structural levels. The architecture was seen to be complex enough to account for the widely varying observed behaviors of materials. This recognition in turn implied that the behavior of a particular material could be predicted from close study of its internal architecture.

Such study has been facilitated by a battery of new instruments and techniques that reveal increasingly fine detail. What Sorby had glimpsed through his microscope was the microstructure of steel. In time optical microscopy was followed first by transmission electron microscopy, which resolves details of substructure, and then by scanning electron microscopy, which provides important three-dimensional surface information. X-ray diffraction maps the spatial arrangement of atoms or molecules in a crystal. The very identity of a material's atoms is revealed by various excitation spectroscopies, and bombardment of a material with high-energy particles probes the atomic nucleus.

The newly disclosed internal structure of materials has provided a framework for understanding the solid state in general and individual materials in particular. The combination of theory and analysis with empirical knowledge has led not only to more effective manipulation of natural materials but also to an extraordinary diversity of new, manmade materials: synthetic polymer fibers and plastics, high-strength and high-temperature metal alloys, glass fibers that serve as optical waveguides, magnets made of rare-earth elements, high-strength ceramics, composite materials and the semiconductors that gave birth to the microelectronics industry.

This array of advances has been



CHEMICAL BONDS, determined by the electronic structure of a material, are directly related to a material's properties. The five kinds of bond are shown here highly schematically; in most materials there is some combination of bonds. The ionic bond forms between ions, or positively and negatively charged atoms; oppositely charged ions are attracted to each other. In the covalent bond pairs of atoms share their outer electrons and thus fill their outer electron shell. In a metal all the outer-shell electrons are shared among atoms, moving through the lattice of atoms as conducting electrons. The van der Waals bond is a weak attraction between nearby neutral atoms or molecules. The weak hydrogen bond is mediated by a hydrogen atom that is shared by two molecules.

achieved by what can now be considered an integrated discipline: materials science and engineering. Its practitioners, whether they consider themselves to be scientists or engineers, deal with the relations among structure, properties and performance, and with how those mutual interactions are affected by processing. These terms deserve some definition.

A material has structure: particular arrangements, or configurations, of internal components. To begin with, it has subatomic structure: one studies the locations and densities of electrons and their mutual interactions. Proceeding to the next level, one investigates the organization of atoms or molecules, for example the precise arrangement of atoms in the lattice of a crystalline material. The next structural realm consists of very large groups of atoms that have identifiable characteristics, such as the individual grains of a metal or a ceramic. These groups agglomerate to form the microstructure and in turn the macroscopic structural elements that can be seen with the unaided eye.

A material also has properties: characteristic responses to external stimuli. For example, the mechanical properties of a material, such as strength and elastic modulus, relate deformation to an applied load or force. Does a steel rod subjected to an increasing force applied in a particular direction bend or break? When? If it bends, does it spring back when the force is no longer applied? Such electrical properties as conductivity and its reciprocal, resistivity, are responses to the stimulus of an electric field. A solid material has a wide range of other properties of interest, including thermal, magnetic, optical and chemical.

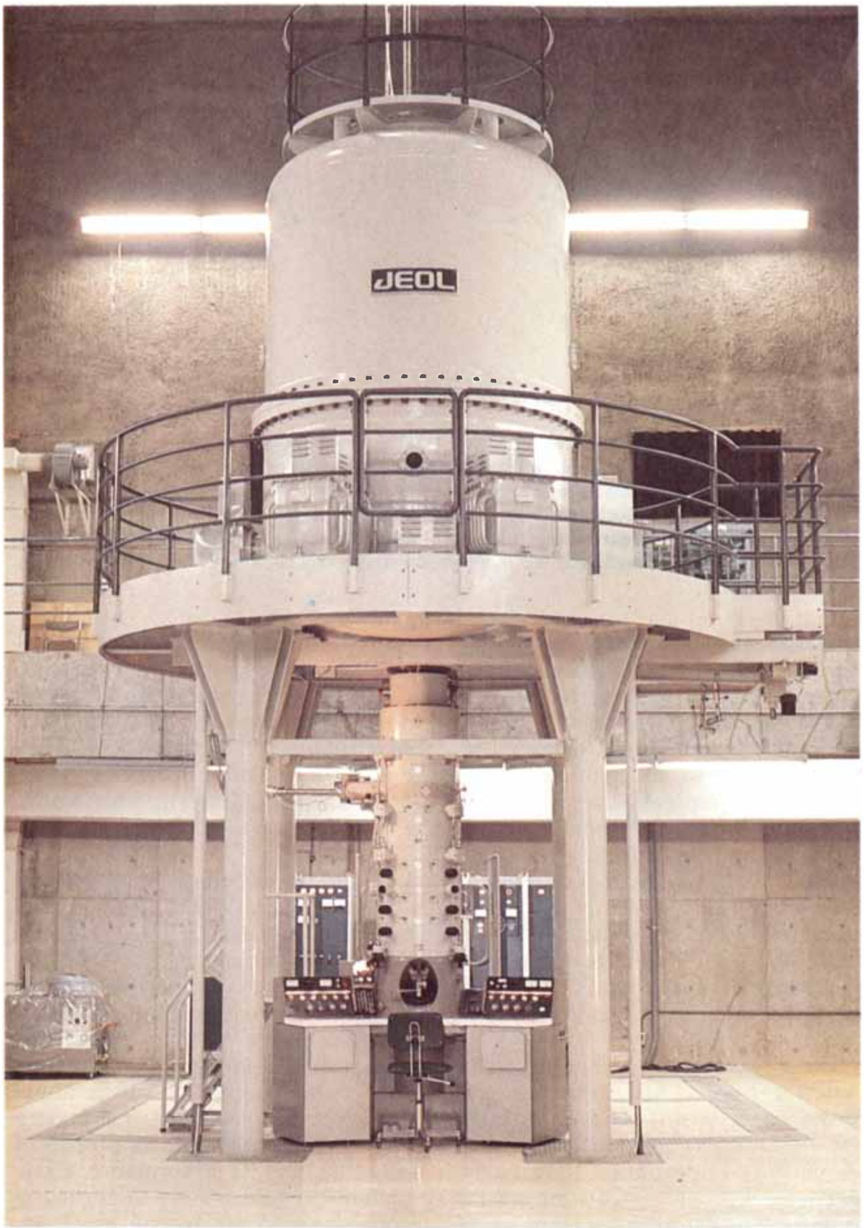
The structure and properties of a material largely determine its performance, or how it behaves in actual use. Performance introduces a new set of concerns. For example, to know the mechanical properties of a material is to be able to describe the response of that material to a well-defined "idealized" force. In actual use the force may instead be far from well defined. It is likely, in fact, to be a complex system of varied and variable forces that may have competing, additive or synergistic effects.

Structure, properties and performance are tied together by processing, which can be defined as the control or modification of any level of the internal structure of a material in order to achieve desired properties and performance. Processing, in other words, is what makes it all happen.

Materials scientists have for the most part studied structure and properties and the relation between them. Materials engineers, on the other hand, have concentrated on the relation of structure and properties to performance and on processing techniques that improve performance. Now, as more becomes known about how processing can modify a material's structure, and thus its properties and ultimately its performance, scientists are becoming more interested in processing and are having more impact on it. Their findings have been translated into improved processes in areas ranging from steel manufacture to the production of pure glass fibers. A striking example of scientific input is the development of ways to grow the very large single crystals of the semiconductor silicon from which integrated-circuit chips are made.

Scientists ordinarily prefer to work with idealized materials and simple structures or processes. Their results can nonetheless lead to at least a qualitative understanding of more complex materials. Then too, a theoretical model based on an idealized material can be modified to fit a real technological material. For example, much of the early work of solid-state physicists on metals dealt with crystalline solids: materials composed of an infinite, orderly and rigid array of atoms. The orderly array provided a convenient framework for theories and could explain some properties of metals. It was observed, however, that the actual strength of materials was orders of magnitude less than their theoretical strength based on ideal crystalline solids. It became clear that such properties as strength are sensitive to deviations from ideal-crystal structure.

The realization led physicists to the concept of defects. They found that some atomic sites in an array are left unoccupied under normal conditions, that atoms can occupy what should be holes in the array, that one kind of atom can substitute for another kind and that atoms actually vibrate rather than being stationary. Moreover, there can be deviations from the exact periodicity of the crystal array: dislocations, stacking faults, grain boundaries and so on. In time theories were developed to explain the origin of the defects and their role in altering properties. That in turn has made it possible to manipulate the generation of intentional defects and so obtain desired structures and properties. In the case of noncrystalline materials it is much harder to predict the effect of processing. In glass and in most polymers, for example, a small deviation in processing can have a large and unexpected effect on properties and performance.



HIGH-VOLTAGE ELECTRON MICROSCOPE at the Institute for Materials Science of the University of Antwerp can resolve the atomic structure of a sample of material. Electrons accelerated to an energy of 1.25 million volts by a Cockcroft-Walton voltage multiplier in the large tank are focused on the sample by electromagnetic lenses in the column below. The image is examined on a fluorescent screen or recorded on a photographic plate. The high acceleration of the electrons, which enables them to penetrate a thick sample, makes this kind of electron microscope effective for analysis of materials.

Much as crystallography provided a framework for understanding the crystalline structure of real materials, the science and laws of thermodynamics have provided information about what is called the equilibrium state of a material. Thermodynamics determines the effect of environment, in particular of pressure and temperature, on the equilibrium state (the rest state) of a material or any other system. The laws of thermodynamics relate the energy of a system and the environmental variables to describe the system's equilibrium state or a change of state. The equilibrium state, then, is the minimum-energy state of a material for a given temperature, pressure and composition. To take just one example, a body in which a temperature gradient has been imposed prefers to have a uniform temperature and will seek to attain it.

Now, a material that is a mixture of two or more component substances may consist of two or more phases: homogeneous, physically distinct and mechanically separable portions, the analogues of, say, oil and water. (In this sense most good structural materials are composites.) Under idealized conditions the phases are in equilibrium. Again, however, in practice one operates under conditions that are not idealized ones. When a material, be it clay or steel, is heated, worked and cooled, it may well pass through various nonequilibrium states. Indeed, most of the technologically important materials have long been manipulated through nonequilibrium states and in due course put into service in a "metastable" state.

The quenching of a steel, for example, retards the equilibrium reaction involving its iron and carbon atoms and in effect freezes the material into configurations in which it does not really "want" to be. Although differential quenching has long been practiced in the manufacture of high-grade steels, for lack of theoretical knowledge it was primarily by altering chemical composition that one could effectively control the processing of established materials and attempt to synthesize new ones. Eventually increased understanding of idealized equilibrium states, and of the particular deviations from the ideal that result in metastable states, made it possible to vary structural configurations through the control of processing.

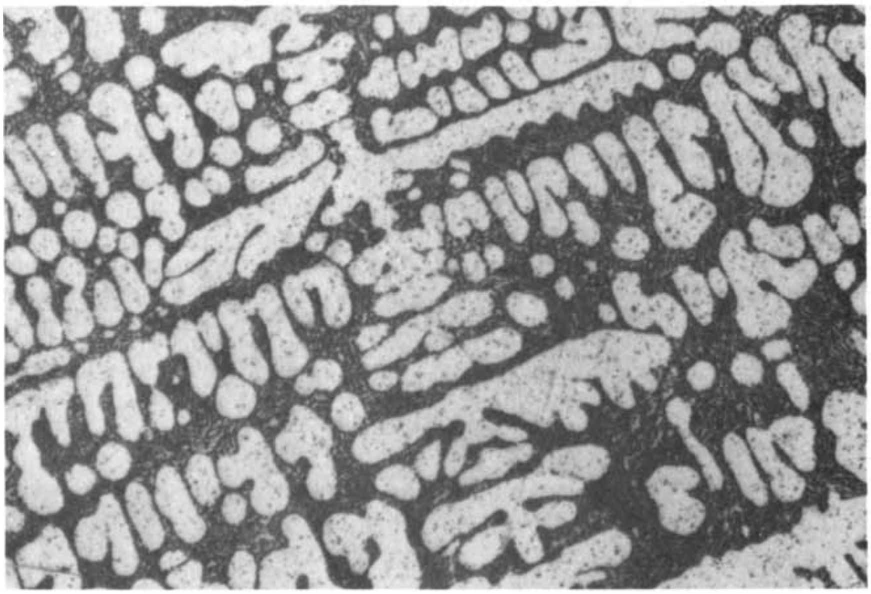
A number of different specialized thermal treatments for steel in the solid state, for example, give rise to a variety of structural configurations. Included are such metastable phases as martensite, which is notable for its strength and hardness. As a matter of fact, it is the extent to which the properties of steel can be readily varied by thermal treatment that makes steel effective in so many technological applications. Other metallic alloys, as well as ceramics, glasses and polymers, can also be altered structurally by differential processing to achieve specialized properties.

It is primarily by the processing of materials far from equilibrium that a range of truly new structures—indeed, of new atomic configurations—are being brought on the scene, tailor-made to have new properties and perform in new ways. One of the conceptually simplest ways to push a material far from equilibrium is to cool it at an extremely high rate.

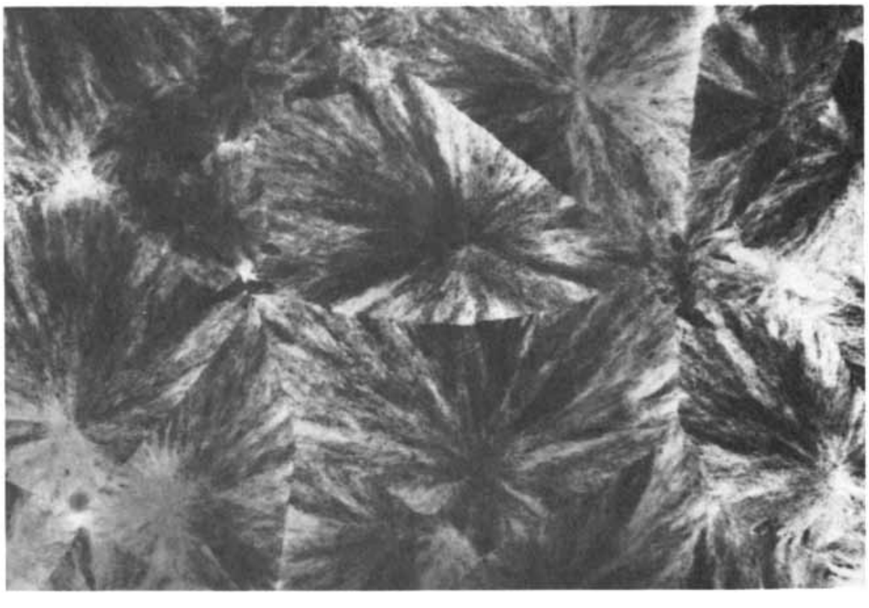
In 1960 Pol E. Duwez of the California Institute of Technology and his co-workers devised "splat" cooling, in which a small amount of molten metal is propelled at high velocity to impact on a very cold surface. They showed that metals could thereby be cooled from the liquid state at rates on the order of 10,000 degrees Celsius per second (compared with typical rates of hundreds or perhaps 1,000 degrees per second), and that such rapid quenching would give rise to an entire range of new characteristics.

By now a variety of techniques have been developed for very fast cooling. In all of them rapid heat transfer is accomplished by impelling, squeezing or spraying molten metal into sudden contact with an extremely cold medium. At least one dimension of the rapidly cooled solid is therefore restricted: the solid is in the form of either a powder, a ribbon or slivers. There are some specialized applications for which such forms are appropriate, as in the case of recorder heads made from rapidly cooled ribbons or sheets. In most cases, however, the particles or ribbons must be consolidated into more appropriate bulk forms.

One of the more striking results of fast cooling is its effect on microstructure. In a micrograph of an alloy cooled at ordinary cooling rates coarse, branching crystal forms called dendrites can be seen. These forms arise because one phase solidifies first when a multicomponent material solidifies. As the solid phase grows, local conditions of heat and mass transfer at the growing interface tend to generate dendritic shapes, the spaces between



CONVENTIONALLY CAST aluminum-silicon alloy is magnified 385 diameters in a photomicrograph made by Thomas H. B. Sanders, Jr., of Purdue University. Two "phases" are evident. The lighter phase (which has a lower silicon content than the darker one) has the typical dendritic (treelike) morphology of an alloy cooled at a relatively low rate.



RAPIDLY COOLED aluminum-cobalt alloy is magnified 125,000 diameters in an electron micrograph made by Sanders. The material, solidified as a "melt-spun" ribbon, was cooled at the rate of about a million degrees Celsius per second. There was not enough time for separate phases to form and the resulting "nonequilibrium" material has only a single, microcrystalline phase. Feathery elements are differently oriented microcrystals.

which are ultimately filled in by the phase or phases that solidify more slowly. The spacing of the dendrites decreases as the rate of cooling increases. (The correlation between dendrite spacing and cooling rate, incidentally, provides an indirect measure of the rate at which a sample has been cooled—a value that can be difficult to establish with precision.)

The finer microstructures obtained by moderate increases in cooling rate display new properties. Now the cooling rate can be pushed to a million or even a billion degrees per second. Under such conditions the formation of separate phases is completely suppressed. Instead extremely small single-phase microcrystals are formed, or even an amorphous, glasslike structure. When one couples control of chemical composition with the wide range of structural control made available by rapid solidification, the potential for developing new properties is practically unlimited. By manipulating these variables one can not only improve a material's strength, hardness, toughness and resistance to wear and corrosion but also specify its behavior in a magnetic field.

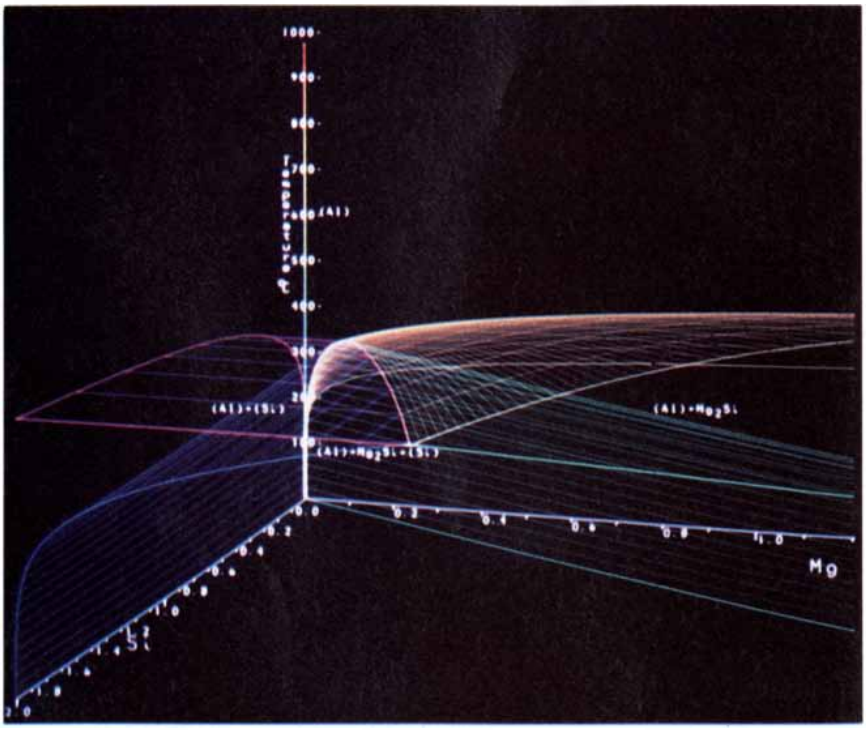
A line of research leading to a quite different kind of structural modification was initiated in 1970 by Leo Esaki and Raphael Tsu of the IBM Thomas J. Watson Research Center. They proposed that it might be possible to synthesize a "modulated" structure. It had been known for a long time that many minerals and alloys display what are termed long-wavelength chemical modulations: periodic defects or variations that are superimposed, in the case of a crystalline material, on the basic crystal lattice. Esaki and Tsu suggested that if one imposed an artificial periodicity on a semiconductor crystal—a periodicity one or two orders of magnitude larger than its natural lattice spacing—the resulting material ought to have novel and potentially valuable electrical and optical properties.

In the past 15 years much effort has been directed toward fabricating such modulated structures and investigating their properties. Most of the work has been done with crystalline semiconductor "superlattices" made of alternating thin layers of two different semiconductor materials. One of the more promising techniques has been molecular-beam epitaxy (MBE), by means of which exquisitely thin layers of different semiconductor materials are deposited successively almost as if by a spray gun. Beams of atoms or molecules of the materials are emitted in turn from heated effusion cells, or crucibles, and are directed against a substrate on a temperature-controlled substrate holder in an ultrahigh-vacuum chamber. The result is an epitaxy: an oriented overgrowth, in which each successive layer tends to (but does not quite) assume the lattice orientation of the layer under it. The modulation, in other words, is both chemical and structural.

The characteristics of MBE uniquely satisfy the stringent requirements for an effective semiconductor superlattice. The low growth rate makes close control of the thickness of each layer feasible. The rather low temperature at which deposition takes place minimizes the interdiffusion of the two materials, so that their interfaces are clean and abrupt. The fact that growth takes place in two dimensions, or plane by plane, makes it possible to generate surfaces that are smooth at a near-atomic level.

MBE is not yet a production-line technology for the manufacture of integrated circuits, but it may be soon. Even as production people work toward that end, interesting questions about the growth and the electronic structure of superlattices are being investigated by experimentalists and theorists.

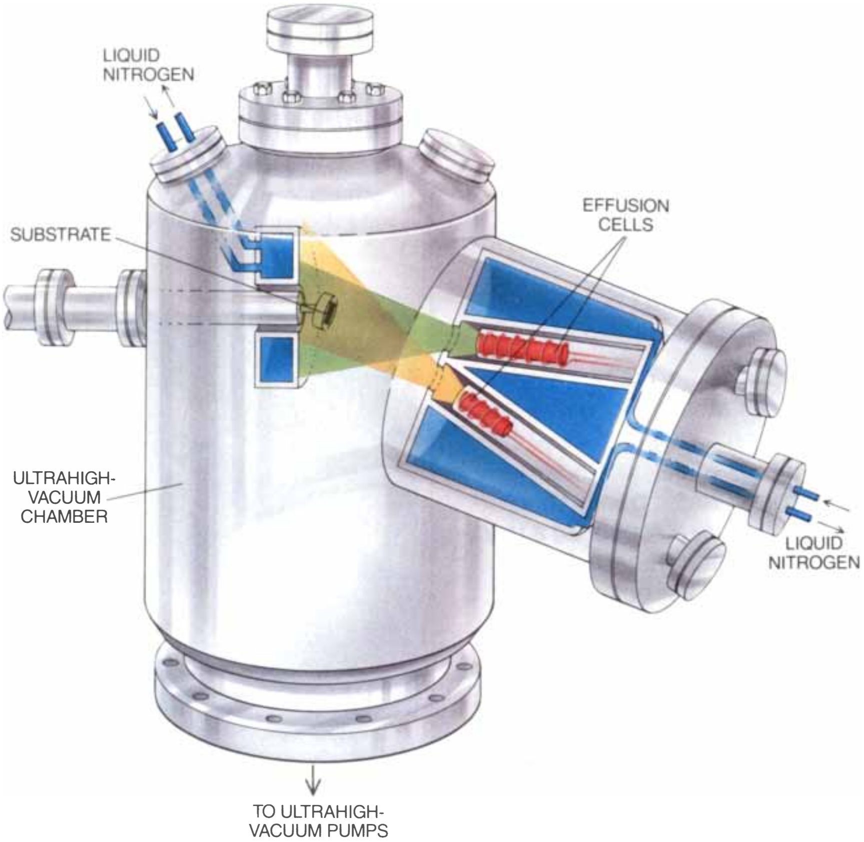
For example, in a high-magnification electron micrograph of an interface one can in effect see the individual atoms of the two different semiconductors. (One actually sees images formed by the diffraction of electrons from each atom's electron cloud.) It can be seen that the inevitable strain at the interface between these mismatched lattices is accommodated by a regular array of "misfit" dislocations. Just how do such interfaces between adjoining layers affect the growth of these structures? Again, the basic role of periodicity in determining the electronic properties of solids is put to new tests in the artificially created world of the superlattice. It should be possible to synthesize solids in which electrons display new ranges of energy and move from one ener-



COLORED SURFACES in this phase diagram developed at Alcoa Laboratories show what phases will be present in an aluminum-magnesium-silicon alloy of a given composition if it is heat-treated at a given temperature. The vertical axis gives the temperature; the two horizontal axes give the content of silicon and of magnesium. The phases are the aluminum (Al) matrix, a magnesium-silicon (Mg_2Si) precipitate and a silicon (Si) solid solution. Within the three-dimensional space above the orange surface only the aluminum phase is present (up to the melting point of aluminum, 660 degrees C.). Both the aluminum and the magnesium-silicon phases are present between the orange and green surfaces, all three phases between the green and blue surfaces and only the aluminum and silicon phases between the blue and purple ones. The interactive computer program that generates the diagram was developed by Dhruba J. Chakrabarti and Sharon L. Ramsey.

gy state to another or from one site to another. Not only the bulk properties of the alternating layers but also the electronic effects of the interfaces themselves will have to be understood if such properties are to be predicted effectively.

The ability to synthesize modulated structures opens up an entire new realm of structures tailored to have desired properties. This will surely be true not only for semiconductor superlattices but also for many other materials that have very different potential applications. MBE should, for example, eventually be able to produce optical coatings that give a mirror specialized responses in specific parts of the spectrum, so-called nonlinear optical devices (which may become elements of optical computers), surface layers for the prevention of corrosion and materials that exhibit specialized responses to a magnetic field.



MOLECULAR-BEAM EPITAXY synthesizes such nonequilibrium materials as superlattices, in which thin layers of different materials are deposited alternately on a substrate that has similar atomic periodicity. The materials are vaporized in ovenlike effusion cells; the beams are directed at the substrate, which is in an ultrahigh-vacuum chamber. Liquid nitrogen keeps surfaces cold, trapping stray gases and helping to maintain the vacuum. The drawing is simplified: MBE systems include control equipment and instrumentation.

As has so often been the case, the progress made in materials science in the past decade or so has been facilitated by a number of improvements in techniques for characterizing materials. Structures have been revealed in ever finer detail by new microscopies. The conventional transmission electron microscope has provided some of the more startling results. The high-voltage electron microscope can resolve structures almost as small as a tenth of a nanometer, or one ten-millionth of a millimeter, in diameter, which is approximately the size of atoms.

Three-dimensional information is provided by the scanning electron microscope and the new analytical electron microscope. The latter is a new integrated system that combines the functions of a conventional transmission electron microscope, a scanning electron microscope and two kinds of analytical spectroscopy. A number of other exotic new microscopies are specifically designed to provide hard-to-get information about the surfaces of materials. The various image-forming techniques are being supplemented by electron-diffraction maps, which make it possible to obtain data on the periodicity of a lattice and other crystallographic information.

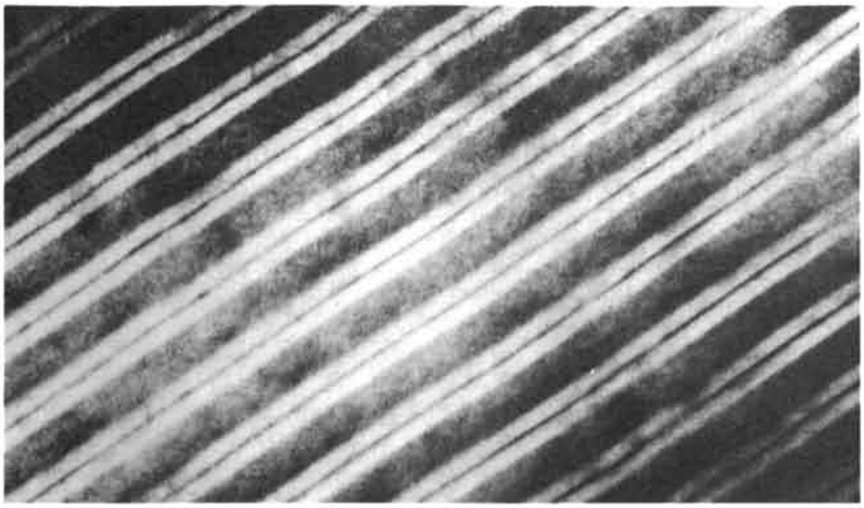
One of the most significant developments in analytical technology has come in the past 15 years with the application to materials research of synchrotron radiation. Radiation is emitted when charged particles in an accelerator such as a synchrotron are deflected by a magnetic field. A synchrotron is therefore a source not only of high-speed elementary particles but also of photons, the particles of electromagnetic radiation. It can take the place of conventional sources of radiation in spectroscopy, which is an important analytical technique for materials scientists.

Spectroscopy examines the characteristic spectrum resulting from the interaction of photons of a particular energy with the electrons of a material. Two basic classes of experiments can be carried out: one can study either the scattering or the absorption of photons. The photons can be in the infrared, visible, ultraviolet or X-ray range of the spectrum depending on what part of the electronic structure is being probed. Synchrotron radiation is of higher intensity and is more highly collimated than radiation from conventional sources, and that makes for more sensitivity in measurement. Moreover, its broad range of energies (from the far infrared to the X-ray region and beyond) makes it possible for the experimenter to select the optimum energy for a given measurement.

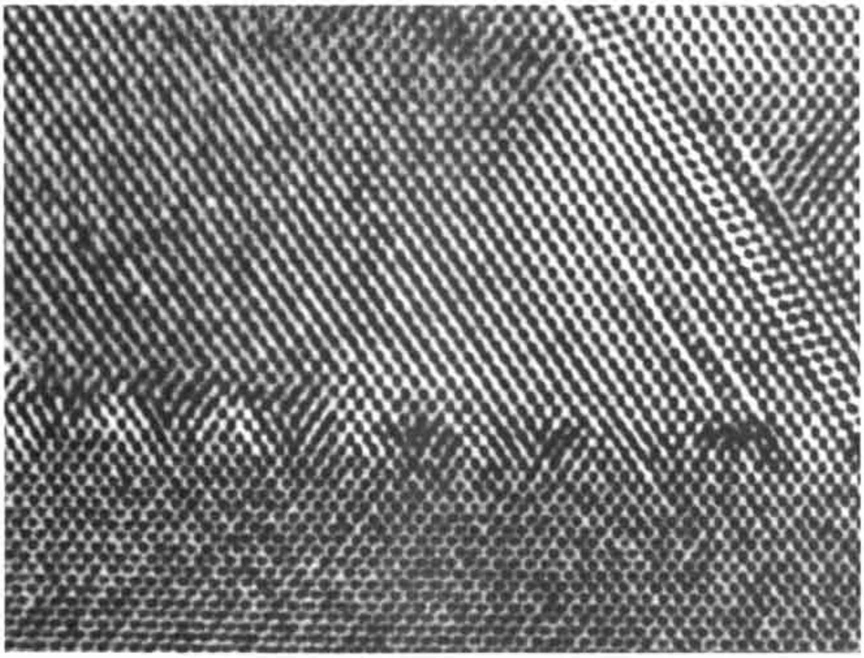
Quite aside from spectroscopy, synchrotron X rays can generate high-resolution X-ray-diffraction maps of details in material structures that could not be studied before. Such details, whether in the bulk material or at the surface, provide information bearing on a material's strength, electronic properties, resistance to corrosion and behavior as a catalyst.

Today there are seven synchrotron-radiation facilities in the U.S., two of which have become available within the past two years: a facility at the University of Wisconsin that provides radiation in the ultraviolet spectrum and one at the Brookhaven National Laboratory that provides far-ultraviolet and X-ray radiation. In recognition of the major potential of synchrotron radiation, a recent National Academy of Sciences report on facilities needed for materials research gave first priority to a new source of high-energy synchrotron X rays.

Powerful experimental facilities are, to be sure, just one element in the advance of materials science. As the articles preceding this one have emphasized, the major stimulus for efforts to improve existing materials and synthesize novel ones has been the critical need of the marketplace for entirely new kinds of performance. As I have tried to show, improved performance stems from the development of processing methods that achieve new structures exhibiting new properties. Sound theory makes it possible to predict those structures and properties, and instrumentation assesses the degree to which the predictions are fulfilled. As the articles that follow this one will make clear, new theory and instrumentation and innovative processing technologies have already yielded an array of advanced materials undreamed of only a few decades ago.



THREE-LAYER SUPERLATTICE built by molecular-beam epitaxy has been enlarged 800,000 diameters in a dark-field electron micrograph, made by Nobuo Otsuka of Purdue, of a cross section. The light bands are zinc-selenium and the major dark ones are zinc-manganese-selenium; each thin, dark stripe is a single unit cell of manganese-selenium.



INDIVIDUAL ATOMS (actually their diffraction images) are resolved in an electron micrograph of the interface between gallium arsenide and cadmium telluride layers in a superlattice. A cross section has been enlarged 5.1 million diameters in the micrograph, which Otsuka made with the million-volt instrument at the Tokyo Institute of Technology. The lower part of the image shows gallium and arsenic atoms, the upper part cadmium and tellurium atoms. "Misfit" dislocations accommodate strains at the interface.

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Electronic and Magnetic Materials

Soon semiconducting chips employed in high-speed logic operations will be imprinted with more than 100,000 transistors, and chips in a computer's memory will store up to 16 million bits of information

by Praveen Chaudhari

The worldwide sales of the electronics industry will be approximately a trillion dollars by the end of the century. Estimates place its current sales above $200 billion, which is roughly equal to the gross national product of India and is larger than the G.N.P. of every country in the world except the top dozen or so.

How can the spectacular growth of the electronics industry be sustained? The answer ultimately lies in its ability to continue to make its products indispensable to society. Although that task requires progress to be kept up simultaneously on several fronts, including manufacturing and marketing, advances in materials science are surely crucial and fundamental. In this article I shall write about the materials technologies that are most essential to the operation of semiconductor devices. I shall also briefly discuss magnetic materials and how they are employed to store information. I must emphasize, however, that the materials discussed here are not the only ones in which progress is required for the electronics industry to grow; other materials have played and will continue to play an essential part as well.

Perhaps the most familiar device fabricated from semiconducting electronic materials is the transistor. Ever since its invention in 1948 workers have sought to miniaturize this most fundamental of electronic components. The motivation is twofold. As transistors shrink in size, electronic systems can be made smaller and the sophistication of the equipment can be increased. This is particularly important for systems such as satellites and missiles, in which size, weight and power requirements are severely constrained. In addition, small transistors are generally faster and cheaper than large ones—a natural consequence of increasing the level of integration and a fact of enormous importance to the computer industry.

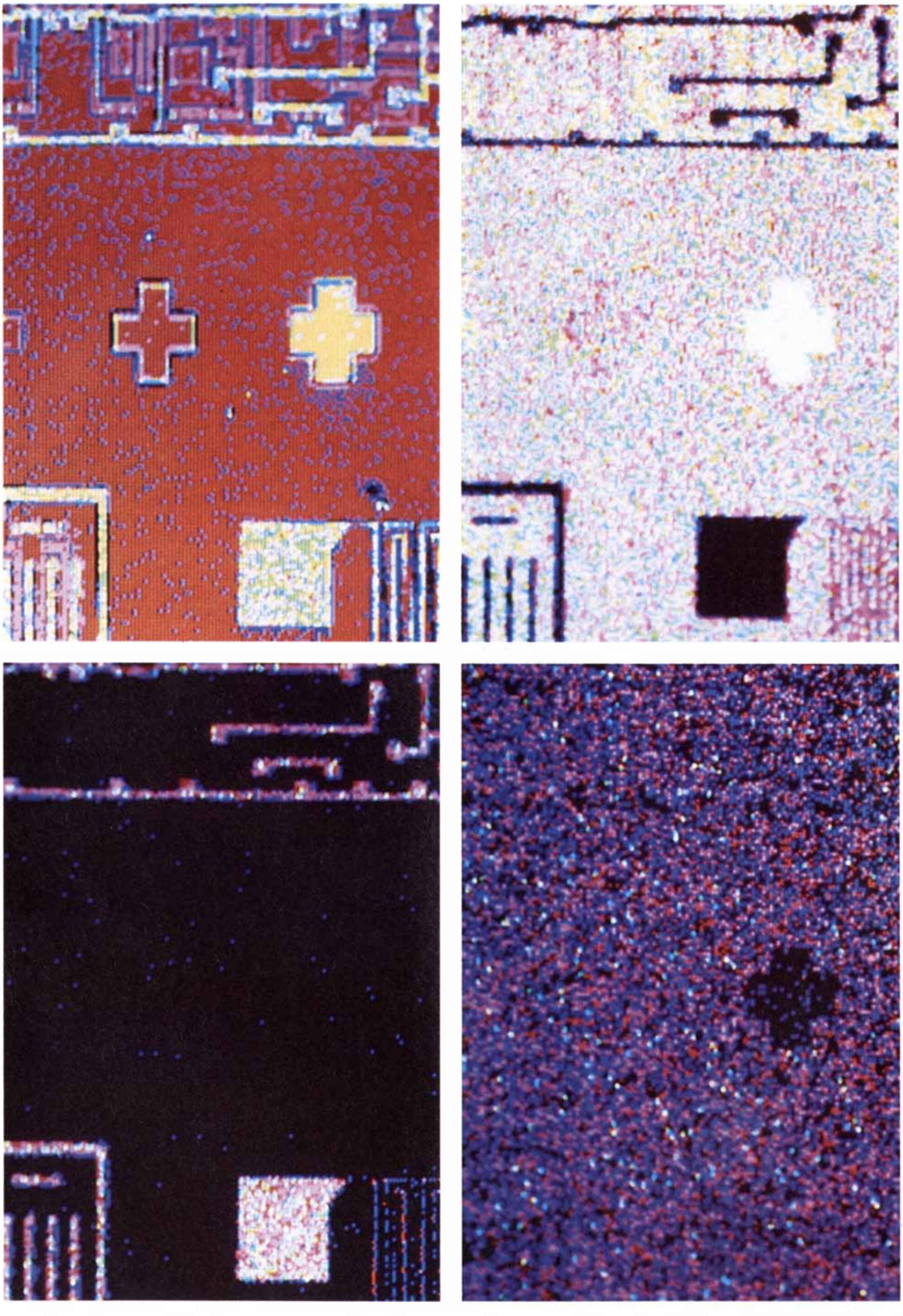
The rate at which transistors have been miniaturized is remarkable. The line width, or smallest feature size of a circuit, has decreased dramatically over the past quarter century. A typical line width in 1960 was 30 micrometers, or 30 millionths of a meter. Today line widths are commonly on the order of one micrometer, or about one-75th the width of a human hair. Most recently half-micrometer line widths have been achieved. They represent an important step in the development of semiconducting chips with more than 100,000 transistors used for carrying out high-speed logic operations and chips capable of storing up to 16 million bits of information. (A bit, or binary digit, is the fundamental unit of computer information, equivalent to the result of a choice between two alternatives such as "yes" or "no" and "on" or "off.")

Extrapolations based on the historical trend suggest that line widths of .1 micrometer will be reached, at least at the research and development level, in the mid-1990's. Many theoreticians believe such a line width represents a serious limit in the design of electronic circuits; devices smaller than .1 micrometer may require modes of operation different from the present ones. As the end of the century nears, therefore, the development of transistors is broadening into areas other than miniaturization. Workers are exploiting exotic effects to increase the speed of the present generation of transistors. They are experimenting with novel combinations of materials and new transistor designs. They are even beginning to dream of "biochips."

Two kinds of transistor now common in the electronics industry are the bipolar transistor and the field-effect transistor, or FET. Both are central to the operation of computers. Bipolar devices are the basic building blocks of a computer's central processing unit, the part of the machine that does operations on data. FET's, on the other hand, are generally the basic building blocks of a computer's memory. FET's are also increasingly used to carry out logic operations in small- to medium-size computers. The division is a consequence of the fact that in switching operations bipolar transistors are faster than FET's.

In spite of the differences between the two devices, bipolar transistors and FET's share similar principles of operation [see "Microelectronic Circuit Elements," by James D. Meindl; SCIENTIFIC AMERICAN, September, 1977]. In effect a transistor is a switch: by applying electric charge to a particular region of the transistor the device can be turned "on" or "off." When a transistor is on, an electric current flows from one region of the device to another; when the transistor is off, the current flow is stopped. In the case of a bipolar transistor, by applying electric charge to a region called the base one can control the flow of current between two regions known as the emitter and the collector. The cor-

THIN-FILM RECORDING HEAD represents an important advance in information-storage technology. The device is used to store and retrieve data on the magnetic disk of a computer's permanent memory (*see illustration on page 143*). The head, which is about the size of the period at the end of this sentence, was made by evaporating an electrical conductor (*spiral*) on a ceramic substrate. The curved structure at the top carries current to and from the spiral. The head can detect weaker magnetic fields than a head containing a wire coil can. Consequently data can be packed more densely on magnetic-storage disks.



responding elements of an FET are known as the gate, source and drain [*see illustrations on page 141*].

Both bipolar transistors and FET's are currently made from the same kind of semiconducting material: silicon. In a crystal of pure silicon very few electrons are available to move about because they are needed to hold the crystal together. A silicon atom has four valence, or outermost, electrons that are available for bonding and other interactions. In solid silicon each atom is surrounded by four other atoms arranged in the shape of a tetrahedron; the atoms are bound to one another by shared pairs of valence electrons. The material can be made to conduct by doping, or injecting, it with impurity elements.

The performance of bipolar transistors and FET's alike depends to a large extent on the quality of the original silicon crystal. Crystals that are relatively uniform and defect-free can be grown by a technique known as the Czochralski process. A crucible is filled with silicon and held at a temperature about 100 degrees greater than silicon's melting point, which is 1,685 degrees Kelvin (1,958 degrees Celsius). A small seed crystal of silicon is then dipped into the molten silicon. The seed crystal is slowly pulled up from the melt and is simultaneously rotated. As it is pulled up, silicon atoms in the melt attach themselves to it. The crystal grows in size until it reaches its final proportions, approximately 150 millimeters (six inches) in diameter nowadays and possibly as much as 200 millimeters in the foreseeable future.

Larger diameters are difficult to realize because unwanted fluid currents in the molten silicon introduce nonuniformities in the crystals. The currents arise from temperature and density differences in the melt. To slow the fluid motion, investigators are exploring the possibility of immersing the crucible in magnetic fields. In addition, since gravity is one of the causes of the currents, a tempting experiment to carry out on a space station would be the growing of crystals with an extremely large diameter.

COMPOSITIONAL IMAGES of the same part of an integrated circuit reveal the spatial distribution of elements in the chip. Starting at the upper left and proceeding clockwise, an electron image of the chip and elemental maps of its silicon, phosphorus and aluminum are shown. The images were made by bombarding the chip with a beam of electrons. Some of the electrons scattered off the surface; the electron image is a record of such backscattered particles. Other electrons in the incident beam excited atoms to emit X rays. Since the particular wavelength of the emitted X rays is a signature of each element, the different materials could be mapped. The images were made at the Institute for Materials Science of the University of Antwerp.

After the crystal is grown it is sliced and polished to make wafers. The wafer is usually so smooth that the height of its surface varies by less than 10 angstrom units, or 10 ten-billionths of a meter, from point to point. Such a distance corresponds roughly to the length of a chain of 10 hydrogen atoms placed end to end.

The crystal is then ready for processing into an integrated circuit. The procedure for processing a simple FET illustrates the complexity of the task facing the manufacturers of future devices. First the wafer is heated to approximately 800 degrees K. in the presence of oxygen. The heating causes a thin layer of silicon dioxide to grow on the surface of the wafer. Then the surface is covered with a polymer coating known as a photoresist. An integrated-circuit pattern is formed in the photoresist by exposing it to either electromagnetic radiation or charged particles and etching away the unwanted parts. The etching process exposes a clean silicon surface in selected and defined areas.

Next the wafer is doped with ions (charged atoms) to generate regions just under its surface that have electronic properties different from those of silicon. One of the deleterious effects of ion bombardment is that it damages the silicon crystal. To restore the crystal to its original condition, it is annealed, or slowly heated. The annealing step is done simultaneously with the growth of another layer of silicon dioxide (approximately 300 angstroms thick) on the surface of the exposed silicon. This oxide, unlike the first one, must be able to withstand the high electric fields—on the order of several hundred thousand volts per centimeter—applied to the gate during the operation of the FET.

A number of different metals and alloys are then deposited on the wafer. Three techniques are generally employed: vacuum evaporation, sputtering and chemical-vapor deposition. In vacuum evaporation the atoms to be deposited are generated by evaporating them from the surface of a hot metal placed in a vacuum. Alternatively, the atoms can be generated by sputtering, or dislodging, them from the surface of a metal with a beam of heavy ions (charged atomic species with large numbers of protons and neutrons). In chemical-vapor deposition organometallic gases deposit their metals either by decomposing or by reacting with the wafer surface.

After the wafer is built it is cut into a number of chips, each of which may contain as many as one million transistors (for memory applications). The chips are then mounted on a ceramic package. The package until recently was generally regarded as a simple technology. This is no longer true. In fact, the cycle time of a machine, or the time it takes to process a set of instructions, is determined not only by the chip but also by how long it takes the signal to go from one chip to another. In a large machine the travel time can be quite long compared with the average time of an operation performed on a chip [see "Microelectronic Packaging," by Albert J. Blodgett, Jr.; SCIENTIFIC AMERICAN, July, 1983].

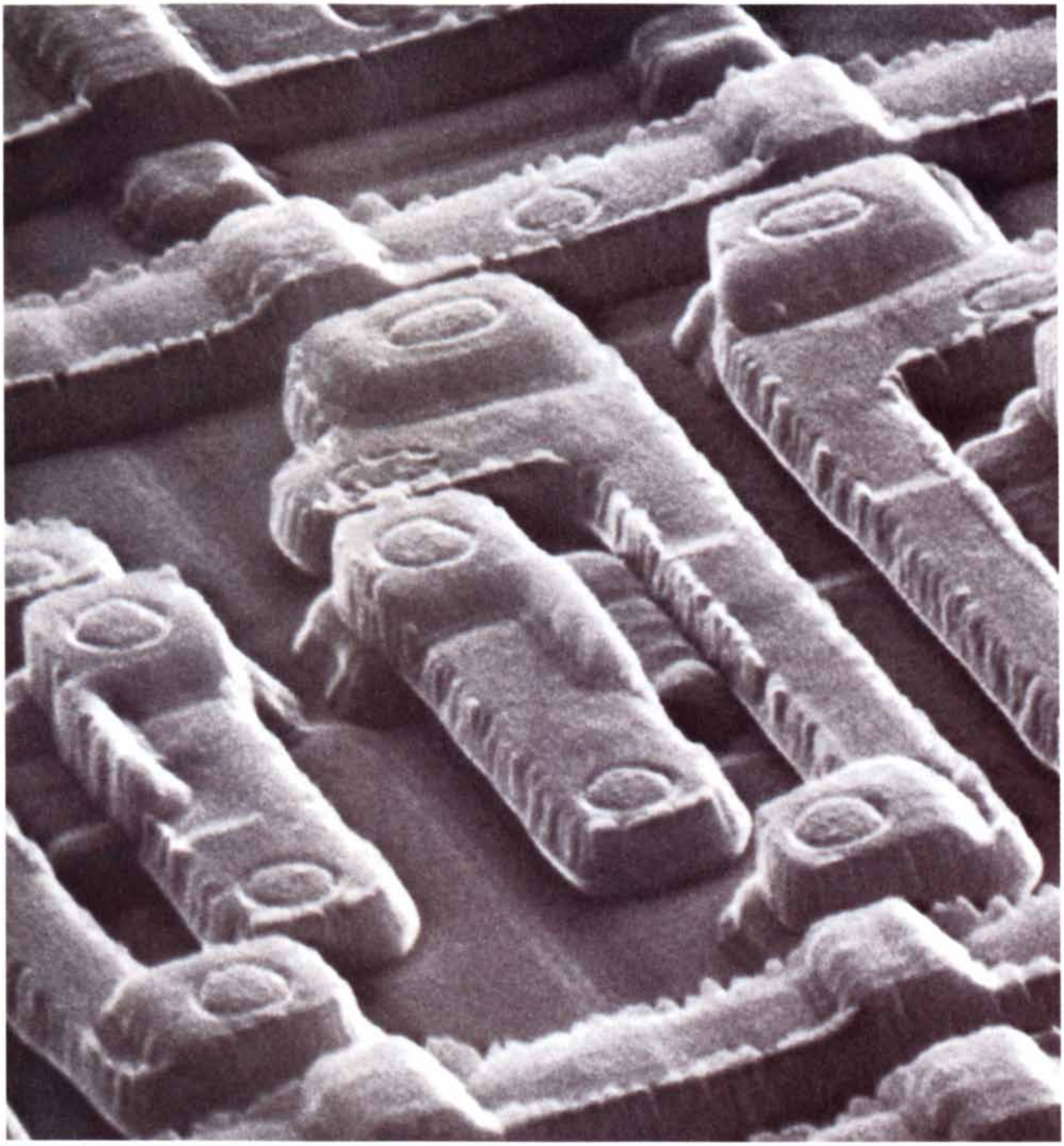
The speed of the present generation of integrated circuits can, as I have mentioned, be increased by miniaturizing their components. To etch progressively smaller structures on semiconducting chips, special approaches will have to be followed. In particular, the relatively long wavelength of light is poorly suited to cutting extremely sharp features into the photoresist that covers the wafer. One way this limitation can be skirted is by substituting beams of high-energy electrons. The wavelength associated with the electrons is a fraction of the diameter of an atom. It is this approach that made possible the fabrication of the half-micrometer line-width structures I mentioned above.

In another approach under consideration, very-short-wavelength X rays would be used to cut circuit elements into chips. The X rays would be produced by synchrotrons, machines that accelerate charged particles to high velocities by means of electric and magnetic fields. As the particles are accelerated they throw off large amounts of electromagnetic radiation. The wavelength of the radiation can be "tuned" by changing the acceleration of the particles. For X-ray "lithography" to be effective, mask-alignment techniques would need to be developed. In addition, present-day synchrotrons are quite large; tabletop models would be desirable.

Plasma etching is another evolving technology expected to play an increasingly important role in miniaturization. In this technique a plasma beam—a "soup" of charged particles containing approximately equal numbers of positive ions and electrons—is aimed at the surface of a chip. By varying the direction of the beam it is possible to remove atoms at particular locations on the chip. In addition to having a high degree of directionality, plasma etching has the advantage of not involving liquids, which can cause corrosion or can become entrapped in cavities. It has a disadvantage too: the energetic beam can damage the surface of the chip. Either plasmas with lower energies or techniques for eliminating surface damage will have to be developed.

Scaling down the size of a device puts forward other technological challenges for today's engineers. For example, as an FET is made smaller the silicon dioxide insulator on its surface becomes thinner. If the insulator becomes too thin, the electrons applied to switch the gate on and off can "tunnel," or leak, through it to the silicon substrate below. If they do, the performance of the device (as designed nowadays) suffers. Also the higher fields can permanently destroy the insulator. It therefore becomes important to find insulators that can withstand the necessary electric fields.

Another problem that can develop when a large number of circuit elements are imprinted on a single chip is electromigration: the unwanted move-



DENSEST LOGIC CIRCUIT ever imprinted on a semiconducting chip is shown here in part. The line width, or smallest feature size, of the circuit is .5 micrometer: approximately 150th the width of a human hair. Most chips, in contrast, have line widths of one or two micrometers. The high density was achieved by making the circuit with the help of an electron beam instead of a light beam. Matthew R. Wordeman, April M. Schweighart, Robert H. Dennard, George A. Sai-Halasz and Walter W. Molzen of the IBM Thomas J. Watson Research Center built the device, which is part of a larger circuit known as a Programmable Logic Array.

ment of material through interconnection lines, the "wires" that join the elements to one another. Although the amount of current that flows through an integrated circuit is small compared with the amount that flows through a household appliance, the current density, or amount of current per unit of cross-sectional area, is several orders of magnitude larger. In general, current density increases at least by the factor by which a device has been miniaturized; in some cases current density increases by the square of the factor of miniaturization.

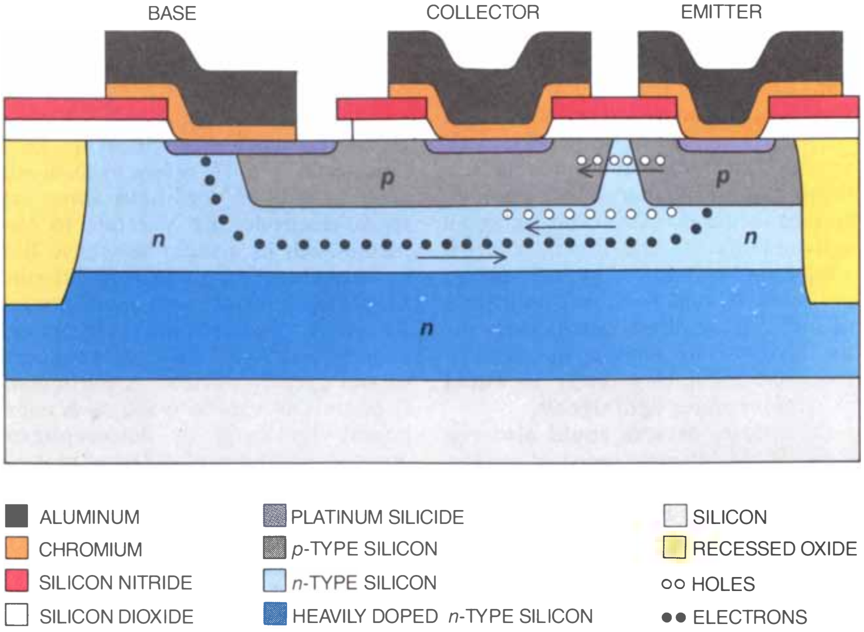
A typical electronic line having a cross-sectional area of 10^{-8} square centimeter might carry a current of a hundredth of an ampere unit; this corresponds to a current density of a million amperes per square centimeter. A wire going from an electrical outlet to a household appliance, in contrast, might have a cross-sectional area of 10^{-4} square centimeter and carry a current of one ampere: a current density of a mere 10,000 amperes per square centimeter.

The current densities of integrated circuits are so large that they can actually lead to the motion of material from one part of a metal line to another. Once such electromigration begins it is self-perpetuating: since the current density in depleted regions is larger than the current density in enriched regions, more material migrates from the depleted regions to the enriched ones. The effect can result in a catastrophic failure of the metal line.

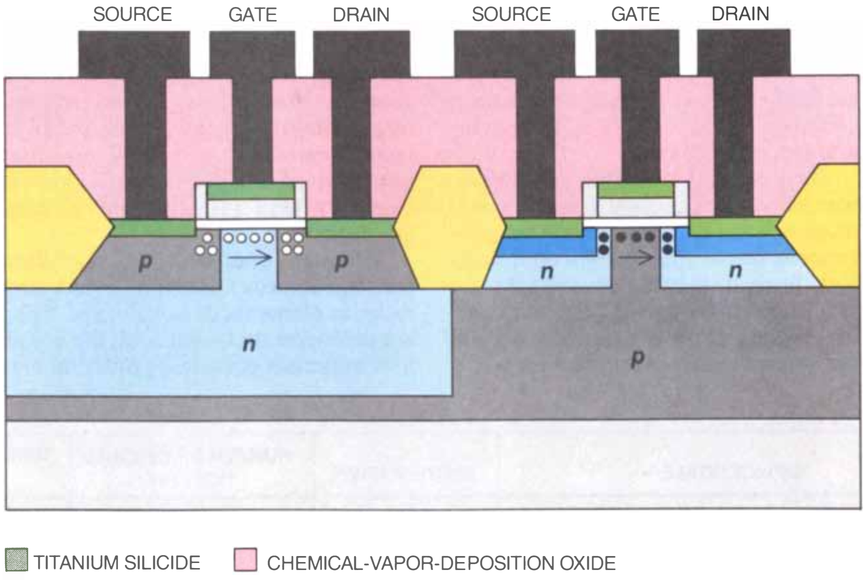
To nullify the consequences of electromigration, metal lines are now made from alloys of copper and aluminum. The copper tends to retard the unwanted spread of aluminum atoms by precipitating a copper-aluminum compound along the paths of most rapid diffusion. In spite of the success of copper-aluminum lines in the present generation of devices, however, they are not expected to slow electromigration to an acceptable level in future integrated chips, which will have even greater densities of circuit elements. The search for new materials to solve the problem continues.

It is conjectured that circuit components could also be made denser—and hence faster—if three-dimensional devices were built. Today most of the action takes place close to the surface of the silicon wafer. The bulk of the crystal serves simply as a substrate. Although it is not clear how much faster three-dimensional devices would be, workers are now exploring the possibility of building circuits up by layering one plane on top of another.

The planes could be built up by



BIPOLAR TRANSISTOR is essentially a switch: by applying electric charge to a region called the base the device can be turned "on" or "off." When the transistor is on, an electric current flows from a region called the emitter to another region called the collector; when the transistor is off, the current flow is stopped. In the *pnp* bipolar transistor shown here the base is made of "*n*-doped" silicon: silicon that contains extra electrons for conducting a current. The emitter and collector are made of "*p*-doped" silicon: silicon that contains "holes," or vacant sites that can move through the crystal just as bubbles move through liquid. Although a hole is not a real particle, it nonetheless carries a positive charge. In the operation of the device the emitter is held at a potential of zero voltage and the collector is held at a high negative voltage. When a small negative voltage is applied to the base, holes in the *p*-doped emitter migrate to the collector. (Some of the holes are also attracted to the base while the modest negative voltage of the base drives electrons to the emitter.) When the small negative voltage applied to the base is reduced to zero, the current flow stops: holes in the emitter no longer migrate to the collector.



FIELD-EFFECT TRANSISTOR (FET) is made by setting into a silicon substrate three elements called a gate, a source and a drain, which correspond respectively to the base, emitter and collector of the bipolar transistor. Two FET's are shown here: a *p*-channel FET (*left*) and an *n*-channel FET (*right*). When a negative voltage is applied to the gate of a *p*-channel FET, holes in the substrate are attracted to it, forming a conduction channel just under an insulating layer of silicon dioxide. The channel allows other holes from the source to flow freely to the drain. When the voltage is removed, the holes in the substrate sink back into the bulk of the material and the current stops. The *n*-channel FET operates the same way, except that a positive (instead of negative) voltage applied to the gate attracts a conducting layer of electrons (instead of holes) under the insulating surface.

means of either vacuum evaporation or chemical-vapor deposition, the traditional techniques by which metals and alloys are deposited on wafers. Layers of silicon would be sandwiched between insulating layers of, say, calcium fluoride. The device would have to be built at low temperatures, however, so that in the process of laying down a given plane the one directly under it would not be damaged by high-energy particles. In one possible application of such a three-dimensional device the top layer would contain optical sensors and the layers under it would process incoming light signals.

Of course, devices could also run faster if the intrinsic speed of switching, or electrical transport, were faster. Semiconductors made from the compound gallium arsenide (instead of the element silicon) inherently have such a superior property. To understand why, quantum-mechanical considerations must be taken into account.

On the scale of atomic dimensions, electrons behave as though they were waves—a specific example of the particle-wave duality of all matter and radiation. When "electron waves" interact with the periodic atomic structure of a semiconducting chip, unusual phenomena can arise. In particular, an electron in a semiconductor behaves as if its mass were much smaller than the mass of an electron traveling in free space. In the case of silicon, for instance, an electron can move as if it had one-fifth the mass of a free electron. The effective mass of an electron in gallium arsenide is, in contrast, about one-fifteenth the free-electron mass. It is this small mass that enables electrons to move faster in gallium arsenide than in silicon.

Theoreticians speculate that transistors made from gallium arsenide could have switching speeds from two to five times as fast as those of silicon transistors. Such transistors could make for faster and more powerful computers. The higher speed of electrons in gallium arsenide also gives promise of devices that can amplify high-frequency communications signals.

Gallium arsenide is just one example of a semiconductor that can be constructed from the so-called Group III and Group V elements of the periodic table. The III refers to elements such as gallium that have three valence electrons; the V refers to elements such as arsenic that have five valence electrons. By mixing different proportions of elements from groups III and V, the electronic and optical properties of a material can be tailored to suit specific devices. A particularly promising way to make such compound devices is by heteroepitaxy: growing thin films of different materials on top of each other, over a crystalline substrate. Heteroepitaxy has already proved invaluable in the fabrication of superlattices: periodic arrays consisting of alternate layers of two different semiconductors. It has also led to the development of novel electronic and optoelectronic devices such as heterojunction bipolar transistors and heterojunction injection lasers.

Three ways of growing epitaxial films are liquid-phase epitaxy, chemical-vapor deposition and molecular-beam epitaxy. In liquid-phase epitaxy thin films are grown on a substrate by cooling a heated solution that contains the wanted elements. Chemical-vapor deposition lays down films by exposing the substrate to a heated stream of gaseous elements or compounds. In molecular-beam epitaxy the films are grown by aiming one or more thermal beams of atoms and molecules at the substrate, which is held in an ultrahigh vacuum. Molecular-beam epitaxy offers perhaps the greatest control over layer deposition, but it is also the youngest of the technologies and is currently used primarily in research laboratories.

Although compound semiconductors can improve existing devices and serve as elements of novel ones, there are problems that come with the use of new materials containing different elements. Since gallium has three valence electrons and arsenic has five, the two metals have radically different electrical and chemical properties. Determining the characteristics of the surface of the compound presents a multibody problem that is hard to solve. As a result the search for suitable materials with which to make contact with the semiconductor has proved difficult. It is also difficult to fabricate gallium arsenide substrates that are free from defects. Moreover, even if all the technical problems are solved, the process of miniaturization would continue, albeit now with materials other than silicon.

Beyond the young but burgeoning technologies I have described so far lie several exotic frontiers. In particular, a most interesting effect arises when devices are scaled down: the motion of electrons inside them can change dramatically. When a voltage is applied across a semiconductor, it subjects the electrons to an electric field and causes them to accelerate. In a large crystal, impurities and defects scatter the electrons and effectively slow them down, so that they merely drift with a constant velocity in the direction of the electric field.

The retarding effects become negligible when the dimensions of the crystal approach the average distance between scattering centers. Crystal defects no longer impede the motion of the electrons, which can now accelerate freely. Transistors made from such crystals should therefore have high switching speeds: they should respond quickly when an input voltage is applied to the base or the gate. Since the fast-moving electrons travel somewhat like bullets fired from a high-powered rifle, the devices are called ballistic transistors.

Even though ballistic transport in transistors has been anticipated for quite some time, it is only within the past year or so that it has been observed at IBM. Multilayer structures,

DEVICE SCALE	ABBREVIATION	NUMBER OF CIRCUITS PER CHIP	SMALLEST FEATURE SIZE (MICROMETERS)	WHEN DEVELOPED
SMALL-SCALE INTEGRATION	SSI	1–100	10	1960's
MEDIUM-SCALE INTEGRATION	MSI	100–1,000	5	1970's
LARGE-SCALE INTEGRATION	LSI	1,000–10,000	3–1	1980's
VERY-LARGE-SCALE INTEGRATION	VLSI	>10,000	<1	1980's
ULTRA-HIGH-SCALE INTEGRATION	UHSI	?	.1–.001	?
MOLECULAR ELECTRONICS	—	?	.001	?

MINIATURIZATION of electronic devices has proceeded at a remarkable rate, as the table indicates. As transistors have been made smaller, more of them have been emplaced on chips. UHSI circuits may be different from the devices described in this article.

including superlattices, might be fabricated in which electrons travel ballistically perpendicular to planes of film as well as parallel to them. Such devices may be particularly fast and compact.

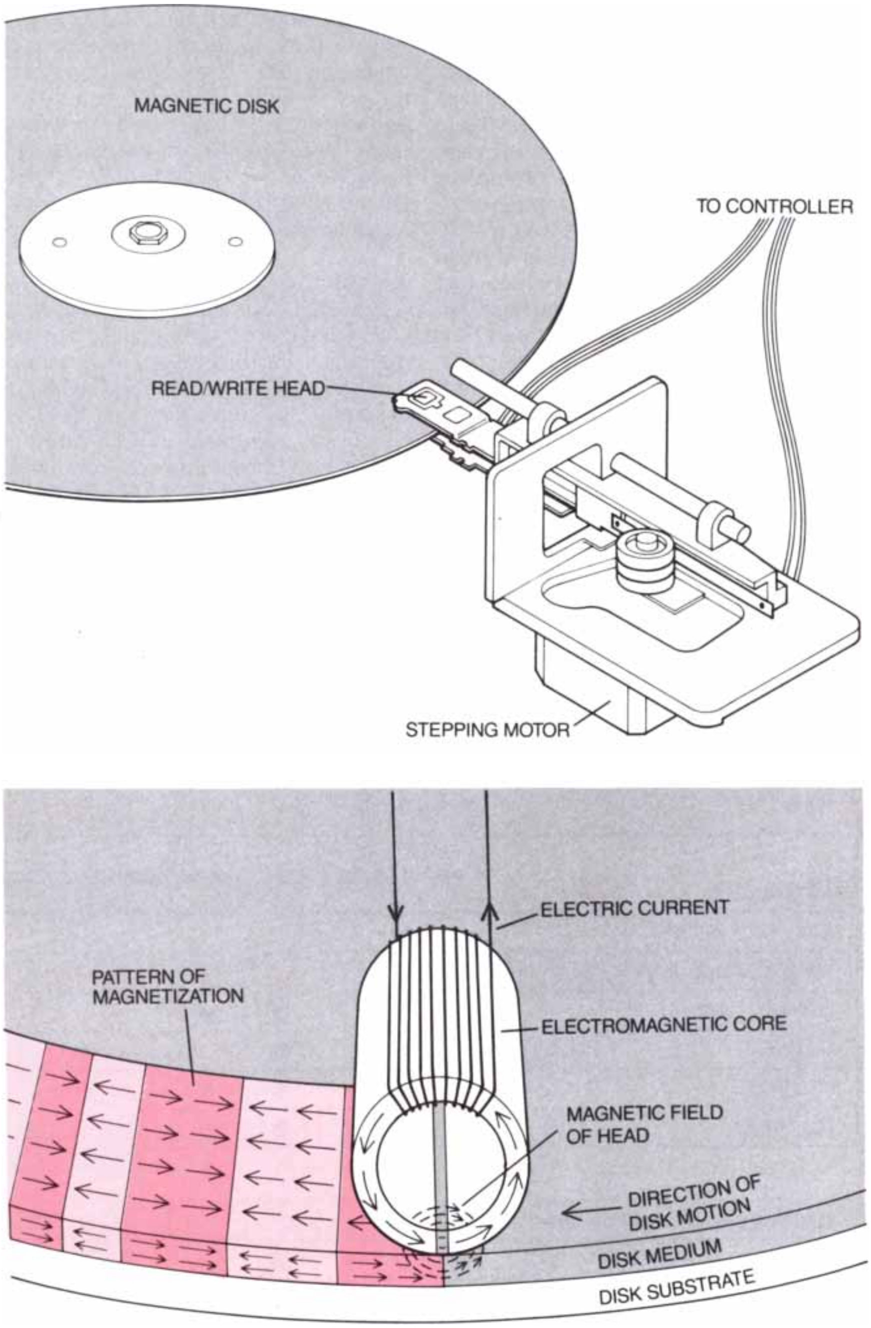
Another device that is generating excitement is the high-electron-mobility transistor, or HEMT. An HEMT consists of many layers of, say, gallium arsenide, whose composition varies from one layer to the next. One kind of layer may, for instance, have few defects or impurities; it is therefore relatively "perfect." Sandwiched around such layers are imperfect layers containing dopant species that can contribute charge carriers. By adjusting the layer composition it is possible to make the carriers from the imperfect layers enter the perfect layers. Since the carriers travel faster in the perfect layers than in the imperfect ones, the sandwich structure makes it possible to have a high concentration of carriers exhibiting high mobility.

Integrated circuits might also be made faster by operating them at low temperatures. As temperature decreases, charge carriers are less likely to scatter from phonons (vibrations of atoms in a crystal), and their mobility is thereby increased. Moreover, harmful, thermally activated processes such as electromigration slow down. In addition the level of background noise—the unwanted electrical signals associated with resistors—decreases. Reduction in noise means that transistors can be run with less power and can be built closer together.

Three approaches to operating electronic devices at low temperatures are now under consideration. Conventional semiconducting transistors are being tailored to perform at low temperatures. The possibility of fabricating transistors from semiconductors and superconductors (materials that conduct electricity with no resistance) is also being explored. Fabrication of transistors exclusively from superconductors is the third and most difficult approach being pursued. All the approaches are currently at the most basic level of research; it remains to be seen whether working devices will be achieved.

Biochips represent another futuristic technology that has gained much popular coverage. There is no precise definition of the term biochip. It can refer to the notion of fabricating a chip from organic (carbon-containing) molecules or from biological or biological-like molecules. It can also refer to the idea that a chip functions somewhat like a natural organism. To date none of the definitions has been physically realized. One can speculate, however, that someday it may be possible to arrange the base pairs in DNA, the genetic material, to store information as complex as a Mahler symphony. Perhaps the scanning tunneling microscope, which has a tip with a single atom on its end, could be employed to store and access such information. Perhaps gene-splicing techniques will be exploited to manufacture the precoded DNA.

Magnetic materials have also figured heavily in the spectacular growth of the electronics industry. The reason is that the preeminent method for storing information in computers—ranging from personal computers to



MAGNETIC DISK AND HEAD (*top*) **are the basic elements of a computer's permanent memory. A typical disk is made of aluminum and coated with a layer of iron oxide. To record data the disk is spun about its axis at a rate as high as 3,000 revolutions per minute. As the disk rotates, the head is brought near and a current is sent through a wire coil wrapped around it** (*bottom*)**. The current generates a magnetic field in the coil, which magnetizes a particular area of iron oxide on the disk. The area retains its magnetization and hence can "remember" data. Stored information is retrieved by reversing the procedure: as the head is swept over the disk the magnetized areas induce a current in the coil.**

large mainframes—is magnetic recording. In one form of the technology a rigid 14-inch aluminum disk coated with iron oxide is spun about its axis at 3,000 revolutions per minute. Such a rate of spin corresponds to a speed of more than 100 miles per hour at the edge of the disk. As the disk rotates, a "head" with which to "read" and "write" data is brought near it. The head consists of a coil of wire wrapped around a magnetic core, which is typically a nickel-iron alloy.

By passing an electric current through the head coil one can record data on the disk. The current generates a magnetic field in the coil, which magnetizes a particular area of iron oxide on the disk. That area retains its magnetization and so can "remember" information. The process by which data are encoded on the disk is known as the write cycle. Information on the disk is read out with the same head by reversing the procedure. As the head moves over the disk, magnetized regions in the disk induce a current in the coil. By measuring the current as a function of time the stored information is obtained.

Even though the processes of reading and writing are based on simple principles, attempts to pack more information onto disks have proved somewhat problematical. As the bit density increases, the magnetic field of each bit decreases. In order to detect the smaller magnetic field, the head must be positioned closer to the disk. Unfortunately smaller head-to-disk spacings increase the probability of occasional but devastating impacts of the head onto the disk. Moreover, since the surface of the magnetic layer is usually quite rough—on the order of 1,000 angstroms—frictional wear is quite common.

To minimize damage from both sudden impacts and frictional wear, lubricants are applied to the disk. Of course, frictional wear could also be reduced if the surface of the disk were made smoother. To build smoother surfaces manufacturers of disk memories are exploring the possibility of exploiting thin-film deposition techniques, in which layers of material are deposited by a plating or evaporation technique. In spite of the successful history of inductive recording, however, the tribology of disks is still more an art than it is a science.

In order to build heads that are more sensitive to magnetic fields, investigators have recently begun to borrow materials and techniques from semiconducting-chip technology. IBM, for example, has introduced a head in which the traditional coil of wire has been replaced by a thin-film conductor deposited as a spiral on the surface of a silicon substrate. The magnetic core of the head is Permalloy, a mixture of nickel and iron. The head, which is now part of the IBM Model 3370 disk memory, can respond to variations in current that occur as rapidly as 100 million times per second. In addition the magnetic field delivered by the head is capable of recording 15,000 bits of information per inch.

In the long run it would be advantageous to eliminate the head altogether. One approach involves the use of magneto-optic materials: magnetic materials that can affect the properties of light. A number of different magneto-optic materials have been investigated over the past two decades. The ones currently in favor are amorphous-alloy films containing rare-earth elements such as gadolinium and terbium and transition metals such as iron and cobalt. While we were working at IBM in the early 1970's, Jerome J. Cuomo, Richard J. Gambino and I first proposed using such materials. Investigators in Japan, in Europe and most recently in the U.S. have since contributed to the development of the materials and their use in the fabrication of prototype storage devices.

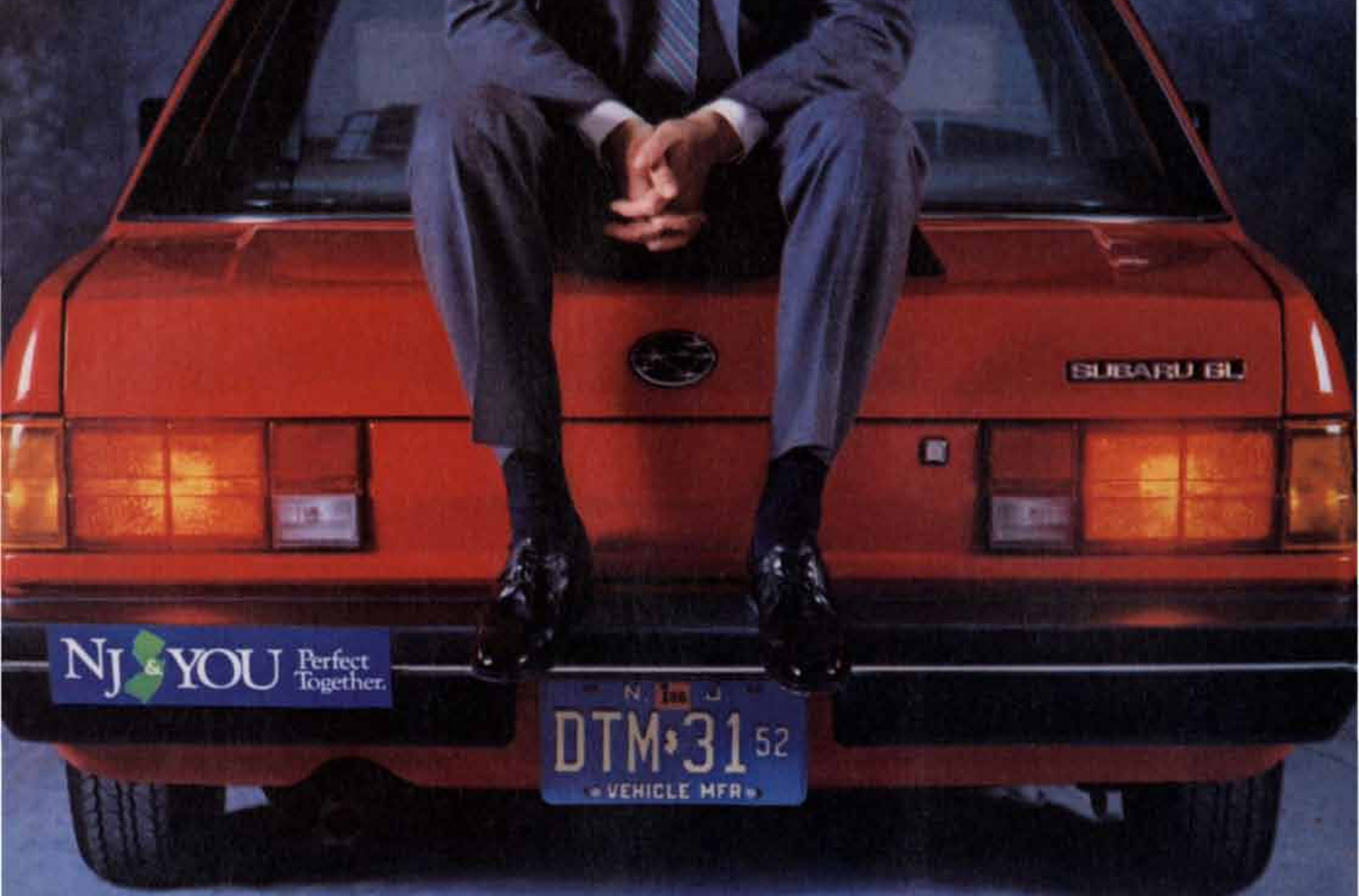
Information is written onto a magneto-optic disk by simultaneously applying a magnetic field and a pulse of laser light to a spot on the disk. The laser light heats the spot while the applied magnetic field magnetizes it. The direction of magnetization of the spot is determined by the direction of the applied magnetic field. To read the data a beam of polarized light is shone on the disk. The polarization of the reflected light is changed according to the direction of magnetization at each point on the disk. By measuring the change in polarization one can access the stored information.

Disk memories based on all-optical elements are also under development. That topic, however, falls beyond the scope of this article.

MATERIALS	CENTRAL PROCESSING UNIT	DISK	TAPE	COMMUNICATION	TERMINAL	DISPLAY	PRINTER	COPIER
SEMICONDUCTORS	●			●		🔴		🔴
SUPERCONDUCTORS	🔴	🔴		🔴				
MAGNETIC MATERIALS		●	●				🔴	🔴
METALS	●	●	🔴	●		●	●	
CERAMICS	●	●	●	🔴		🔴	🔴	
POLYMERS	●	●	●			●		●

TECHNIQUES OF FABRICATION								
VAPOR DEPOSITION/SPUTTERING	●	●		●	🔴		🔴	
ELECTROCHEMICAL	●	🔴		●	🔴			
ION IMPLANTATION	●	🔴		●				
RADIATION CHEMISTRY	●	●		●				
LASER CUTTING/JOINING	●	🔴						

WIDE VARIETY of materials and techniques of fabrication are employed in the various facets of the electronics industry. The black dots indicate materials and techniques now in use; the colored dots show where they may possibly be used in the future.



"MY BUSINESS IS GOING NOWHERE. FRANKLY, I COULDN'T BE HAPPIER."

– Harvey Lamm, President & *CEO,* Subaru of America, Inc.

After many years of accelerating growth in New Jersey, Subaru was thinking of shifting its entire U.S. headquarters to another location.

"We had proposals from Pennsylvania, Delaware, even Southern California," says Mr. Lamm. "But after considering New Jersey's advantages, we decided to stay put."

As a result, the auto importer is building its brand-new headquarters on a 12-acre site in Cherry Hill.

Follow Subaru's lead, and you'll find a state government committed to a creative partnership with business.

A partnership that includes financial incentives and expert help with site selection, zoning, and local regulations. To learn more about how New Jersey can help your business, write Borden Putnam, Commissioner, Department of Commerce & Economic Development, Box CN820, Trenton NJ 08625. Or phone (609) 292-2444.

Is Subaru happy about remaining in New Jersey? "The decision to go nowhere was a smart move for our business," smiles Mr. Lamm.

NEW JERSEY DEPARTMENT OF COMMERCE & ECONOMIC DEVELOPMENT

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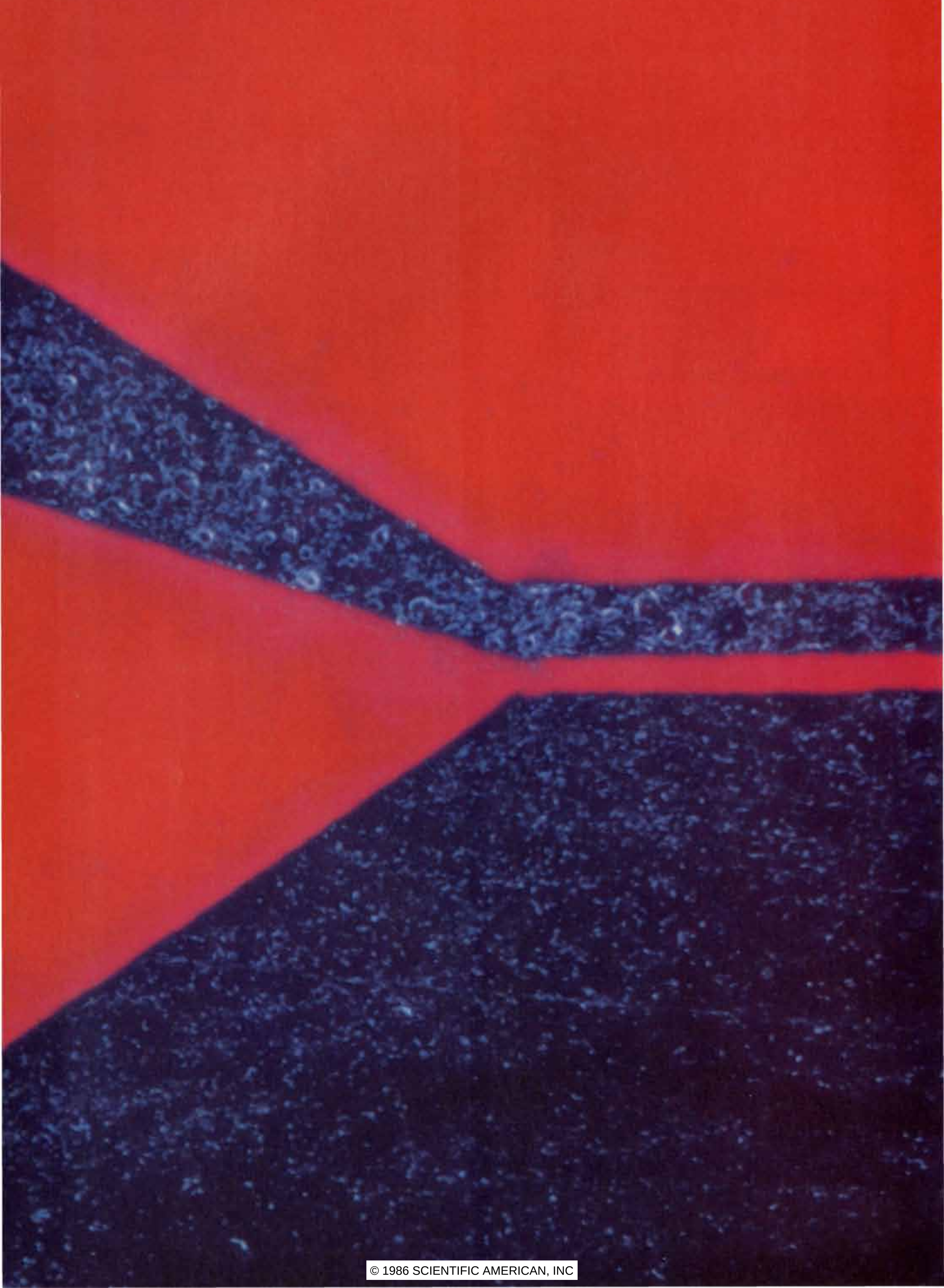


Photonic Materials

The advantages of transmitting light signals instead of electrical ones have led to ultrapure glass, semiconductor alloys only a few atoms thick and "nonlinear" materials that are now revolutionizing communications

by J. M. Rowell

The practical demonstration of an operating laser in 1960 suggested to many people that light might one day replace electrical signals as the common carrier for information exchange. The coherent, monochromatic light emitted by the laser eliminated a major obstacle to light-wave communication: ordinary sources of light cannot be modulated rapidly enough to carry large amounts of information. The enormous information capacity of a coherent source of light made it possible for the first time to give serious thought to the needs of a new technology, analogous to electronics, for generating, transmitting, receiving and processing signals made up of light photons instead of electrons. The technology is now known as photonics. What was lacking in the early years of photonic technology was a practical set of materials that could meet its technical demands.

In the ensuing quarter century the advances in fabricating photonic materials have been comparable to the spectacular successes in purifying silicon for electronics. A case in point is the absorption of light in glass. In the 4,500 years from the earliest known use of glass to the middle decades of this century optical losses caused by absorption in glass were reduced by a factor of 10,000. The improvement led to the familiar transparency of fine lenses, but the remaining absorption was still too great for optical glass to serve as a conductor of light in a communications system. Because of the demands of the communications industry, the optical losses in glass have been reduced in the past 25 years by another factor of 10,000. A window made of the best optical waveguide glass 10 miles thick would be more transparent to light than an ordinary window only an inch thick.

Glass is the most familiar photonic material, but it is only one of several complex materials devised to meet the needs of the most highly developed application of photonic technology: the transmission of information over glass fiber-optic cable [see "Materials for Information and Communication," by John S. Mayo, page 58]. A photonic transmission system must not only guide a light signal over long distances; it must also convert electrical signals into light at the transmitting end and change the light back into electrical signals at the receiving end. For these functions entirely new semiconductor alloys have been prepared, whose properties are quite different from those of silicon. The new alloys are called III-V semiconductors, after the columns of the periodic table to which their elemental components belong. They are made into a broad variety of solid-state lasers and light-emitting diodes that generate a light signal, electro-optical repeaters that amplify the signal as it travels along a fiber and detectors that convert the signal into an electronic pulse. Such devices, perhaps even more than glass, have given substance to the underlying vision of photonic communication.

The evolution of photonic technology has thus led to an intricately symbiotic relation between photonics and electronics: information transmitted purely by photons is generated, processed and stored by devices in which both photons and electrons play essential roles [see "Electronic and Magnetic Materials," by Praveen Chaudhari, page 136]. Purely photonic devices that might be capable of assuming electronic functions other than information transmission have not yet proved to be economically irresistible.

One should not conclude that the emphasis on communication has limited the general development of photonic materials. Their perfection and complexity and the elegant new methods devised to fabricate them represent fundamental advances in materials science that can readily be extended to novel applications, should the marketplace so determine. To choose one important example, it is sometimes convenient to amplify a light signal without electronics, to switch it on or off or to switch it into one of several alternate paths. Such needs have stimulated much excitement about materials generically known as nonlinear: the amount of light they transmit is not proportional to the incident light intensity. In the laboratory a nonlinear optical response has been exploited to create the photonic analogue of a transistor, a purely photonic device that amplifies an incoming signal. By suitably arranging the light incident on a nonlinear material one can also build

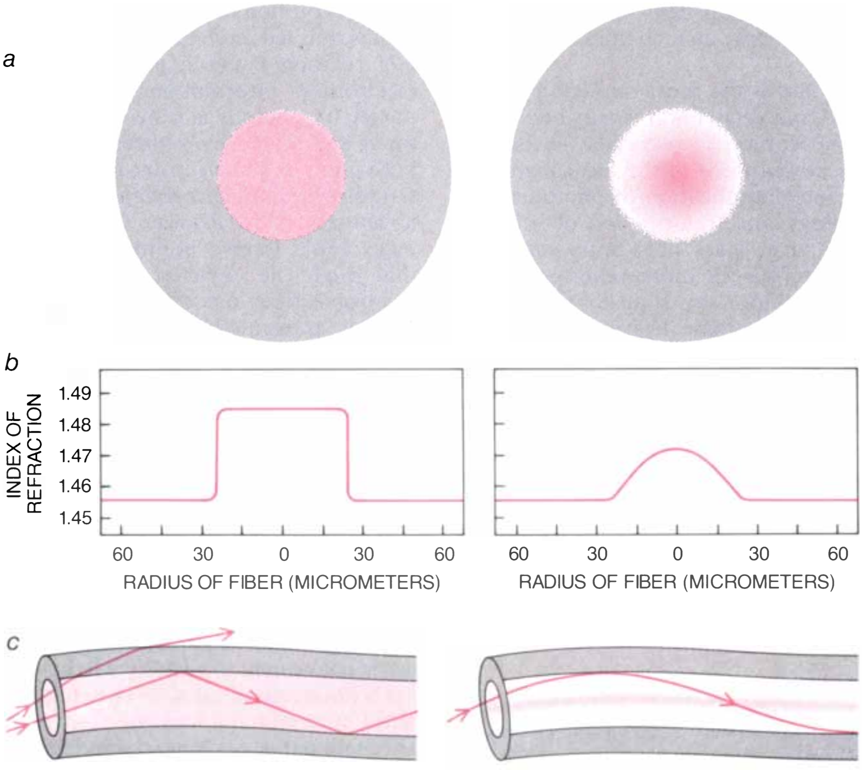
WAVEGUIDE FOR LIGHT, connecting circuit elements on a single chip of optical material, can be defined by photolithography in much the same way electronic circuit elements can. The photomicrograph shows a small region of an electro-optical switch. The optical material is a crystal (*red*) of lithium niobate ($LiNbO_3$); the metallic electrical contacts are shown in blue. A thin film of titanium is deposited on the crystal through a template that outlines the desired waveguide pattern. The titanium is then fused into the crystal; the titanium-doped regions function as paths in the crystal where the speed of light is less than it is in the rest of the crystal. The abrupt change in the speed of light causes rays of light that strike the sides of a waveguide to be reflected back into it; the light is thereby confined. Two such paths have been defined: one under the thin blue strip at the right of the photomicrograph, and the other just below and parallel to the first path, under the horizontal edge of the large blue region. Voltage applied across the metal contacts can cause light to be switched from one waveguide to the other. The hope of many is that photonics will one day be able to duplicate functions other than transmission and routing now carried out by electronics. The magnification is 1,600 diameters.

photonic logic gates, which optically model the properties of the logical connectives *and, or* and *not.* Photonic transistors and logic gates would be basic components of a supercomputer based entirely on photonic technology, which some people believe will one day replace the electronic machine.

For the present, much of photonic technology is devoted to making an efficient, reliable and low-cost link with electronics. The basic materials developed to meet these needs include glass, semiconductors and the nonlinear materials. Photonic materials, like electronic materials, need not be uniform, bulk substances in the traditional sense. Instead they are extremely complicated composites whose makeup and electronic and optical properties vary from place to place in ways controlled almost on the atomic scale. The composition of such materials cannot be considered without also considering how they are fabricated.

Light is transmitted in a fiber made up of a glass core and a surrounding glass cladding; the central core conducts the light signal and the cladding keeps most of the light from leaking away. In the simplest fibers, known as step-index fibers, the glass cladding is a uniform material whose refractive index is slightly lower than that of the central core. (The refractive index of a transparent material is the ratio of the speed of light in the vacuum to the speed of light in the material; the lower refractive index of the cladding implies that the speed of light is slightly greater there than it is in the core.)

Shining a light on the end of the fiber starts light beams along many possible paths in the core and cladding. A beam whose path makes a small angle with the boundary between the core and the cladding is totally reflected because of the difference in the refractive indexes of the two mediums. The beam thereby becomes trapped in the core; the total reflection of light on which the design depends has been well known for more than 100 years. If the light can travel along more than one path, or mode, in the fiber, the fiber is called a multimode fiber. If the diameter of the core is quite small, however, only one beam can be propagated: its path is essentially straight down the center of the core, and the fiber is called a single-mode fiber.

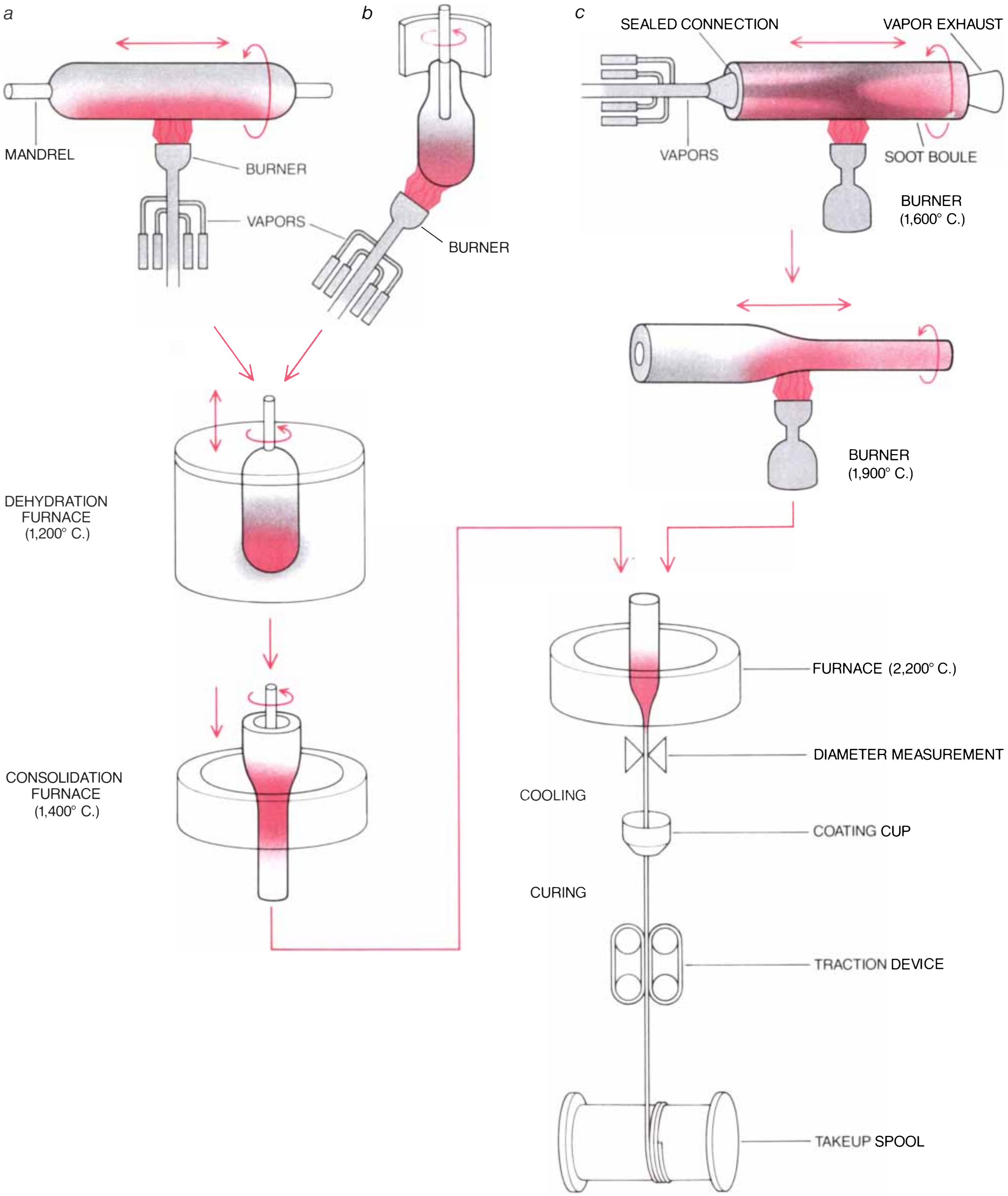


CROSS SECTIONS of two major kinds of optical fiber are shown (*a*); the core of the fiber (*color*) transmits the light signal and the glass cladding (*gray*) confines most of the light. The confinement depends on the variation in refractive index, shown as a tint of color (*a*) and as a graph (*b*). (Refractive index is the ratio of the speed of light in a vacuum to the speed of light in a material.) For the step-index fiber at the left the refractive index changes sharply at the boundary between the core and the cladding; light rays incident on that boundary at a small oblique angle are reflected back into the core (*c*). Rays traveling at an oblique angle to the fiber axis travel farther than rays traveling straight down the core, and so they tend to smear out a signal. By depositing impurities in the glass the refractive-index profile can be given a parabolic shape (*right*). In such a fiber the greater velocity of the rays in the outer core compensates for their longer path.

The refinement of vitreous silica glass (SiO_2) now employed in low-loss optical fiber is approaching the intrinsic limits set by the glass itself. This achievement was not the result of a single insight or invention but the outcome of careful and painstaking work that identified and then eliminated all the factors contributing to optical loss. Impurities such as copper, iron and vanadium have been reduced to a concentration of a few parts per billion. The concentrations of water and hydroxyl (OH) contaminants have been reduced to levels nearly that low. The dimensions of the fiber and the roundness of its core are now fabricated to a tolerance of less than one micrometer over many kilometers of length. Bubbles and surface defects have essentially been eliminated.

Sophisticated designs for the profile, or cross section, of the refractive index of the fiber have also contributed greatly to increasing the distance a signal can propagate in a fiber without having to be amplified. For example, in a multimode fiber the modes traveling at the largest angles to the axis of the fiber travel the greatest distance and are delayed. The delays smear out the signal as it travels along the fiber. The attainable transmission rate is thereby reduced and the useful length of the fiber is limited. To overcome the problem dopants, or impurities, such as boron oxide (B_2O_3) or germanium dioxide (GeO_2) are added to the glass in such a way that the refractive index is made to vary parabolically across the profile of the fiber, from the inside of the core to the core-cladding boundary. The speed of light in the fiber is thus made to increase with the radial distance of a light ray from the center of the core, and so the greater velocity of the large-angle modes compensates for the greater length of their paths. Tailoring the properties of the glass in this way can be called refractive-index engineering.

The limits of glass as a low-loss transmission medium are set by its properties in bulk and on the atomic scale. Because glass is intrinsically a disordered material, a certain amount of light is unavoidably scattered by random fluctuations in the composition and density of the glass. Such scattering is called Rayleigh scattering, after Lord Rayleigh; it varies inversely with the fourth power of the wavelength, and so its effect becomes quite



THREE METHODS are shown for preparing glass cylinders of high purity and for controlling the variation in the refractive index across the cylinder. In outside vapor deposition (*a*) a chloride vapor containing silicon reacts in a gas-oxygen burner and silica (SiO_2) is deposited as a soot on the outside of a rotating glass rod. A long boule of glass is built up by moving the flame or the rod back and forth, and the refractive index of the glass layers is changed by adding other chlorides to the vapor and by controlling the temperature of the burner. At this stage the glass is a porous soot of high purity, except that it contains large amounts of water and negative hydroxyl (OH) impurities. To remove the impurities the soot boule is baked in an atmosphere of helium and chlorine, which reacts with the impurities to drive them out of the boule. The oven temperature is then raised in order to sinter and consolidate the material, and the boule shrinks to its final form as a clear glass free of bubbles. The same steps are applied in vapor axial deposition (*b*), except that a burner builds up a deposit on the end of a rotating rod. In modified chemical-vapor deposition (*c*) a hollow glass tube is heated from the outside by a moving torch, and the vapors flow down the inside of the tube. A reaction takes place near the flame, and the soot is deposited farther along the inside of the tube. The boule is then sintered and shrunk by the moving torch. After such a boule is prepared by one of these three processes, it is drawn into a fiber and coated with a protective plastic.

small at longer wavelengths, toward the infrared region of the electromagnetic spectrum. The sky glows red at sunset because red light is scattered less efficiently by the Rayleigh mechanism than blue light is.

Unavoidable losses on the atomic scale in glass arise because light of certain wavelengths causes atomic transitions to an excited state. Each transition absorbs a photon of light. Ultraviolet light gives rise to electronic excitations: electrons in the glass are promoted to a higher energy state, and a photon whose energy is equal to the difference between the higher energy state and the initial state is absorbed. Infrared light causes vibrational excitations: the bonds between the atoms of silicon, oxygen and dopants that make up the glass can be regarded as springs that can vibrate resonantly at infrared frequencies, and so infrared photons are absorbed.

The mechanism for vibrational absorption suggests a way to reduce optical losses even further, although the fibers now in production meet the demands of telecommunications over all but the longest transmission lines. For atoms of greater mass than the atoms of silicon and for interatomic bonds of smaller "stiffness," the resonant frequency of the infrared absorption is reduced. The lower the frequency, the longer the wavelength. If transmission could be done at longer wavelengths without significant loss, Rayleigh scattering would be smaller and the absorption of light caused by electronic excitations would be reduced. Hence all three intrinsic mechanisms of absorption might be minimized if infrared light at a wavelength longer than the ones in current use were injected into a fiber that had the necessary atomic properties.

Materials such as zirconium fluoride (ZrF_2), arsenic triselenide (As_2Se_3) and potassium iodide (KI) contain atoms of relatively high mass that are weakly bonded, and so they are quite transparent at infrared wavelengths of from 2,000 to 5,000 nanometers. Indeed, because such materials are crystalline, Rayleigh scattering does not take place. The technological difficulties of making fiber from crystalline materials are far from overcome; it has nonetheless been calculated that infrared signals might be able to cross the Atlantic Ocean along such fiber without being amplified.

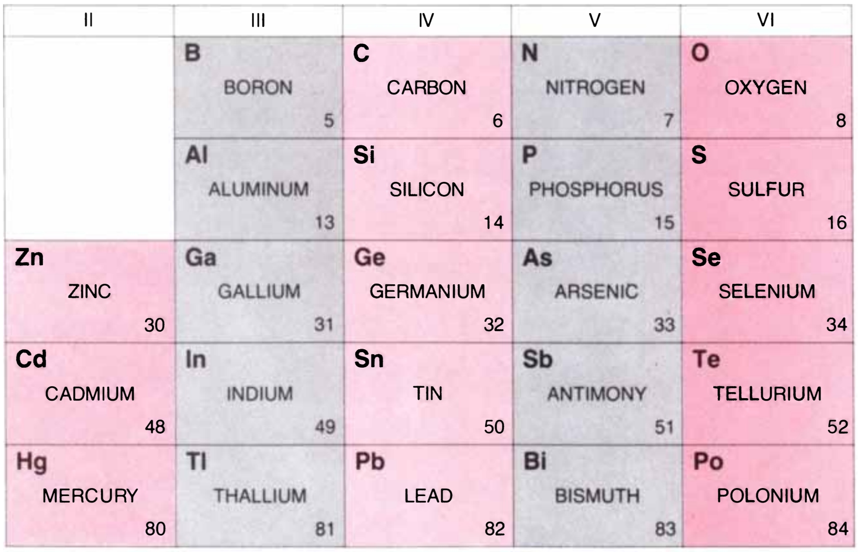
The fabrication of glass fibers, unlike that of crystalline fibers, is an art that has become highly mechanized on an industrial scale. A simple fiber of ordinary silica can be made by inserting a glass rod into a snugly fitting glass tube with a lower refractive index. The assembly is called a preform; the preform is then heated in a flame and drawn down to a diameter of approximately .1 millimeter. The profile of the refractive index in the fiber is identical with the one given to the preform, except that the profile in the fiber is 200 times smaller.

One of the most important advances in making fiber has been the invention of ways to make a preform out of glass of extremely high purity. Three competing methods are now in use, and they all allow the profile of the refractive index to be controlled precisely. In each method a vapor made up of a halide of silicon such as $SiCl_4$ is directed onto or into a glass rod, and silica is deposited on the outer or inner surface of the rod when the vapor reacts with water or oxygen [*see illustration on preceding page*]. The three methods have all been adopted in various production facilities, and there is no clear trend in favor of one dominant choice.

To a large extent the evolution of the materials needed to make transmitters and photodetectors for fiber-optic transmission systems has moved in step with the improvements made in the fiber itself. The earliest fibers transmitted light most efficiently in the near-infrared region of the spectrum, at wavelengths from 800 to 900 nanometers. Both gallium arsenide (GaAs) and the ternary compound gallium aluminum arsenide (GaAlAs) can emit and detect light in that range, and the earliest light sources for optical fibers were built out of them. As fiber improved, the minimum losses for photonic transmissions shifted to longer infrared wavelengths: first to a wavelength of about 1,300 nanometers and, more recently, to a wavelength near 1,550 nanometers. Light emitters and detectors at such wavelengths can be built out of a mixture of four elements, which is known as the quaternary alloy indium gallium arsenic phosphide (InGaAsP).

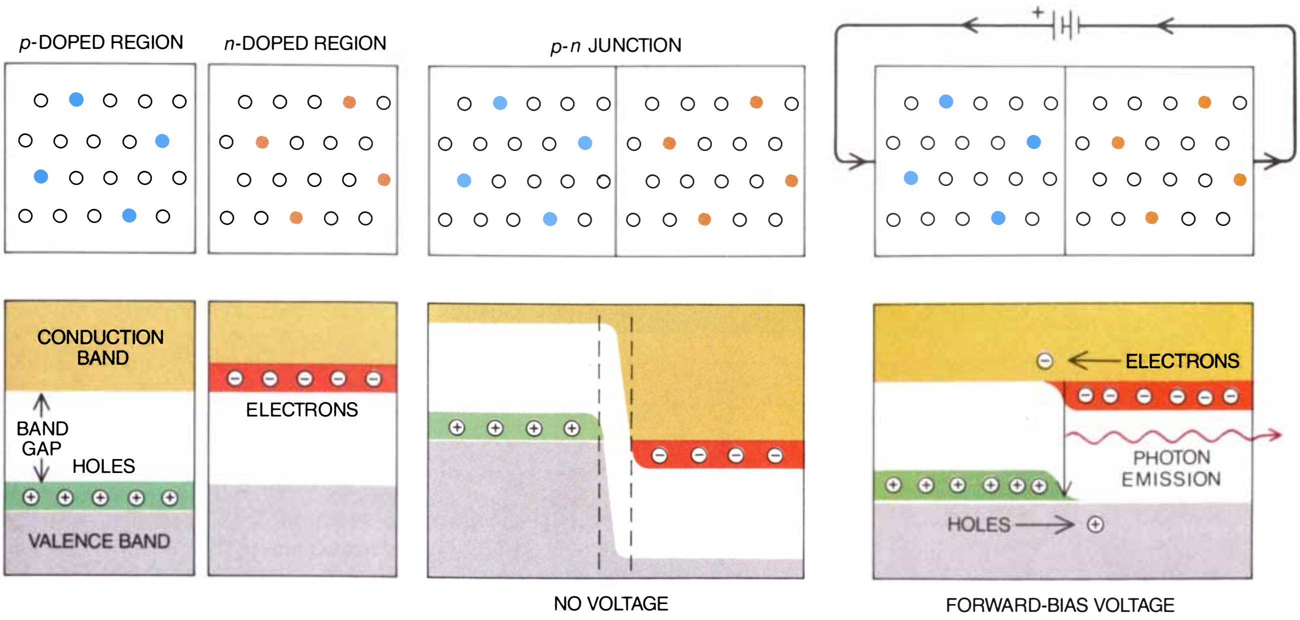
The key factor in the design of such devices is the electronic energy structure of semiconductor materials. As the name implies, a semiconductor conducts electricity better than an insulator and not as well as a metal. In an insulator the valence, or outermost, electrons associated with the atoms in the material are tightly bound to the atoms. A large amount of energy is needed to break the bonds and allow the electrons to move freely through the material as an electric current.

The energy structure of the valence electrons in an insulator can be represented as two bands, or ranges, of energy. At low temperatures all the valence electrons are confined to the first, lower-energy band, which is called the valence band. Above that band in energy is a wide, "forbidden" gap, which is inaccessible to the electrons under the laws of quantum mechanics. Above the band gap is the sec-



II	III	IV	V	VI
	B BORON 5	**C** CARBON 6	**N** NITROGEN 7	**O** OXYGEN 8
	Al ALUMINUM 13	**Si** SILICON 14	**P** PHOSPHORUS 15	**S** SULFUR 16
Zn ZINC 30	**Ga** GALLIUM 31	**Ge** GERMANIUM 32	**As** ARSENIC 33	**Se** SELENIUM 34
Cd CADMIUM 48	**In** INDIUM 49	**Sn** TIN 50	**Sb** ANTIMONY 51	**Te** TELLURIUM 52
Hg MERCURY 80	**Tl** THALLIUM 81	**Pb** LEAD 82	**Bi** BISMUTH 83	**Po** POLONIUM 84

CENTRAL PART OF PERIODIC TABLE lists the elements that combine to form semiconducting binary, ternary or quaternary compounds. The Roman numerals at the top of each column give the number of valence, or outer, electrons found in atoms of the elements listed in the column. For example, silicon atoms have four valence electrons each. In a pure compound semiconductor the average number of valence electrons for each atom must also be four. An element such as gallium from column III can combine with an element such as arsenic from column V, since the average number of valence electrons is four. Similarly, an element such as cadmium can combine with an element such as tellurium. The numbers in the table are atomic numbers: the number of protons in each atom.



BAND-GAP STRUCTURE of a semiconductor selectively doped, or impregnated, with impurities determines its electrical and optical properties. The structure of separated *p*-doped and *n*-doped semiconductors is shown at the left. Dopant atoms deficient in valence electrons leave "holes" in the band of energies associated with the valence electrons in the semiconductor. The positively charged holes readily become free charge carriers that displace electronic energy states in the top of the valence band; they move through the semiconductor the way bubbles move through a liquid. Similarly, in an *n*-doped region the dopant atoms introduce extra valence electrons, which readily become free negative charge carriers in the bottom of the conduction band. If a *p*-doped region is joined to an *n*-doped one, the free holes and electrons begin to migrate across the junction and recombine: electrons in the conduction band fall across the band gap and fill a few holes in the valence band. The recombinations create an electric field across the *p-n* junction, which bends the band-gap structure and prevents further migration and recombination (*middle*). If a voltage is applied as is shown, the band gap across the junction is straightened out (*right*). Electrons are pulled toward the *p*-doped region and holes are pulled toward the *n*-doped region, and the electrons and holes recombine. The recombinations release energy equal to the energy across the band gap. For certain semiconductors that energy is equal to the energy of a visible photon or an infrared one.

ond energy band, which is called the conduction band. An electron in the conduction band can move about freely in the material and so conduct electricity, but the electron can reach the conduction band only if it can absorb enough energy to cross the band gap.

In a metal the valence electrons move freely and at random throughout the material much as the particles of a gas do. The valence band and the conduction band overlap, and so there is no forbidden band gap. Any small voltage applied across the metal can thus impart a net direction to the random motions of the free electrons in the conduction band and cause a current to flow.

In a semiconductor the valence electrons are less tightly bound to atoms than they are in an insulator; the band gap is smaller than it is for an insulator, and so a smaller amount of energy is needed to induce a current. Nevertheless, at low temperatures a semiconductor acts as an insulator unless the material is quite impure. The valence electrons fill the valence band to the top, but there is no overlap with the conduction band as there is in a metal. If enough energy is added to promote an electron to the conduction band, its absence in the valence band leaves a positively charged "hole." A hole acts like a free electron: it can move from atom to atom the way a bubble moves through a liquid. If a voltage is applied across the semiconductor, a current of electrons and a countercurrent of holes can be induced.

One of the most important properties of a semiconductor is that its electrical conductivity can be precisely controlled. By mixing small amounts of impurity with the semiconductor, free electrons or free holes (not necessarily both) can be added to it. For an elemental semiconductor from column IV of the periodic table, such as silicon, each atom in the solid crystal lattice has four valence electrons. Each electron is shared by two neighboring atoms. Thus every atom is surrounded by eight shared electrons, which are just enough to fill the available energy states in the outer electronic shell of the atom.

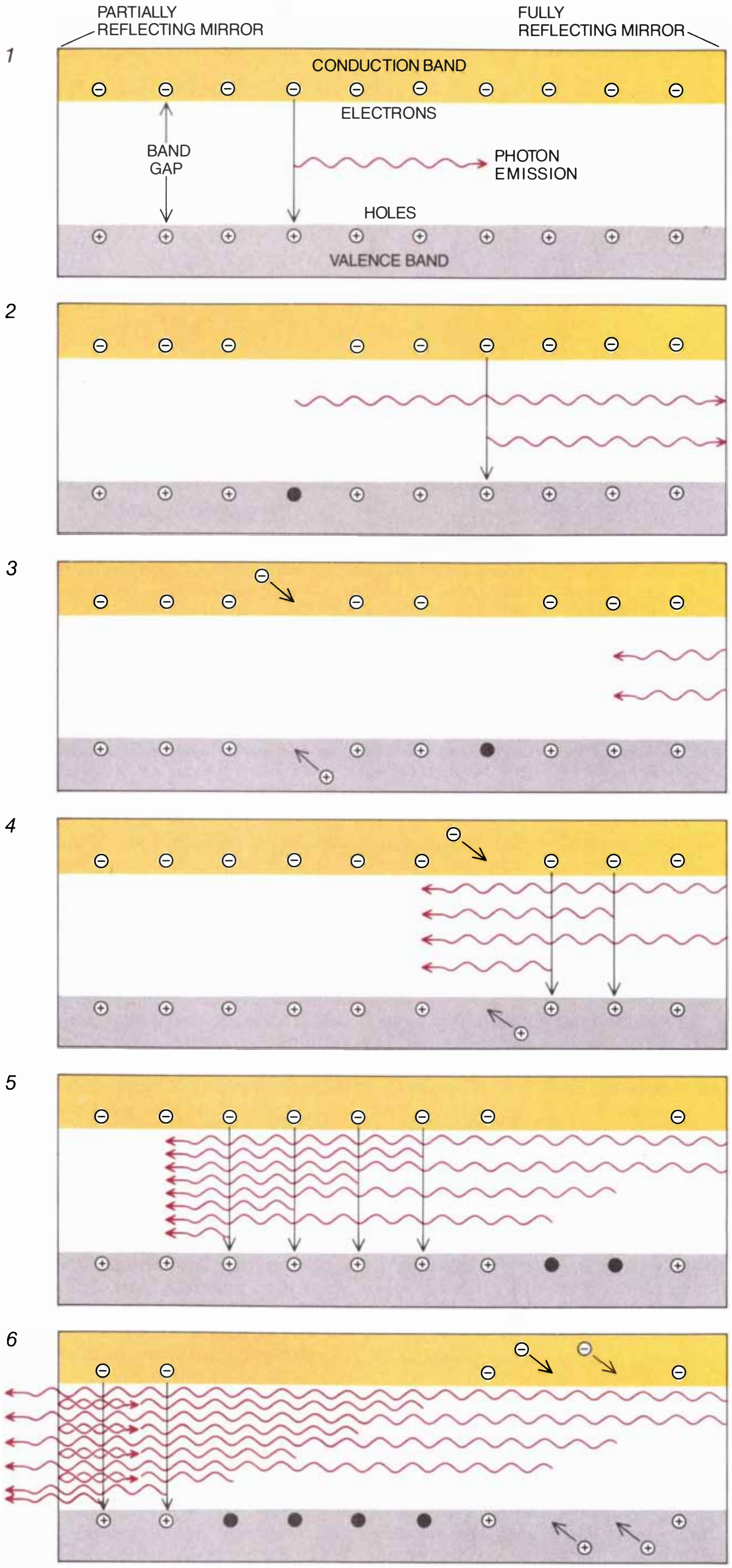
When silicon is doped with a small amount of an element from, say, column V of the periodic table, the resulting alloy contains free electrons: an arsenic atom, for example, has five valence electrons, and so every new arsenic atom introduces one surplus electron that cannot fit into the outer shell of any silicon atom. Since this doping introduces freely moving negative charges, it is called *n*-type doping. Similarly, when silicon is doped with an element from column III of the periodic table, the doped silicon contains free, positively charged holes. For example, a gallium atom has only three valence electrons, so that for every gallium atom there is a hole, or deficit of one electron. Doping with an element deficient in valence electrons such as gallium is called *p*-type doping.

Doped and undoped semiconductors can also be made out of alloys. For example, if an element that has three valence electrons such as gallium is mixed in equal proportions with an element that has five valence electrons such as arsenic, the average number of electrons in the outermost shell of the atoms is still four. Doping an alloy such as gallium arsenide can be done by mixing the two elements in unequal proportions. Semiconductor alloys made out of elements with three and five valence electrons are the so-called III-V materials mentioned above.

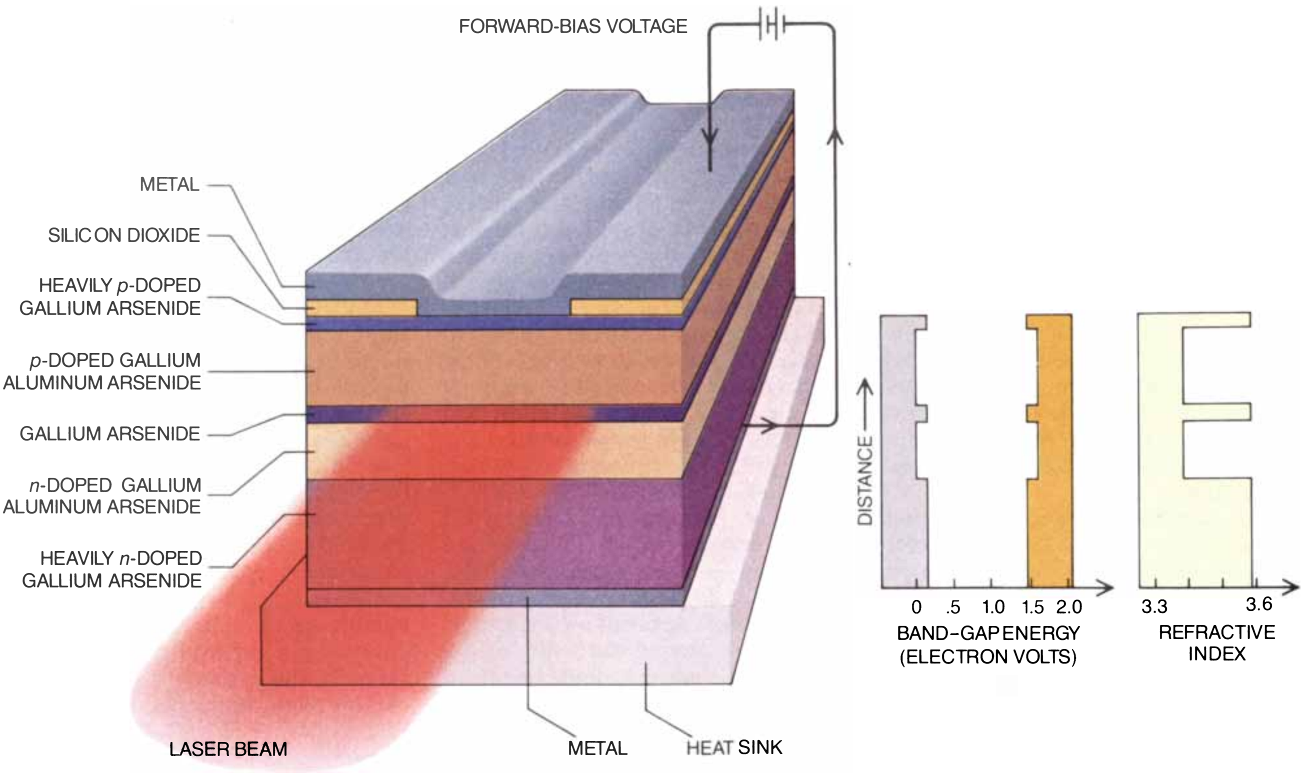
If there is an abrupt change from a *p*-doped region in a semiconductor to an *n*-doped one, a *p-n* junction, or diode, is formed [*see illustration above*]. When the junction is first made, free electrons in the *n*-doped region are electrically attracted to free holes in the *p*-doped region, and the two kinds of particle recombine near the junction. An electron falls from the conduction band into a hole in the valence band, the hole disappears and energy equal to the energy of the band gap is released. After a few recombinations, however, the *n*-doped region acquires a net positive charge and the *p*-doped region a net negative charge. Further migration of electrons toward the *p*-doped region (and of holes toward the *n*-doped region) is thereby halted by electrostatic repulsion, and recombination temporarily ceases.

Imagine now that a positive electrode of a battery is connected to the *p*-doped region and a negative electrode is connected to the *n*-doped region. When a voltage is applied, electrons are pulled across the *p*-*n* junction toward the positive electrode and holes are pulled across the junction toward the negative electrode. They meet in the region of highest density, namely the junction, and recombine. Again each recombination releases energy equal to the band-gap energy.

Both light-emitting diodes and lasers give off light through the recombination of electrons and holes across the band gap. Hence the width of the band gap of a semiconductor determines the wavelength of its light output in a practical device. Because of the detailed structure of the forbidden gap in silicon and germanium, recombination in these materials gives rise mostly to heat. On the other hand, in



LASER-LIGHT EMISSION in a semiconductor is the result of the stimulated recombination of excited electrons in the conduction band with holes in the valence band. In the diagram an excited electron spontaneously recombines with a hole and energy is given off as a photon of light (*1*). Long before further spontaneous emissions can take place the emitted photon stimulates the recombination of a second electron (*2*). The energy of the second emitted photon is equal to the energy of the first, and so, according to the laws of quantum mechanics, their frequencies must also be the same. The two photons resonate with each other and propagate in phase; a mirror at the right end of the semiconductor (*3*) reflects them back through the cavity. As they proceed through the semiconductor they stimulate more recombinations, and a coherent wave is built up (*4*, *5*). A partially reflecting mirror at the left end allows some of the light to escape (*6*). A current driven through the semiconductor supplies a constant stream of new electrons and holes. Above a threshold current the coherent light wave suddenly builds up and the device begins to function as a laser.



HETEROJUNCTION LASER is built up from several layers of semiconductor of varying composition and doping. The band-gap structure of the layers surrounding the light-emitting region is designed to confine both the charge carriers and the emitted light. A larger band gap in the surrounding layers prevents electrons and holes that enter the light-emitting region from leaving it. A lower refractive index in the surrounding layers traps the emitted light in much the same way as it does in the cladding of an optical fiber.

III-V semiconductors such as gallium arsenide or indium phosphide the recombination energy is released predominantly as infrared photons; such materials can therefore serve as sources of photons. It is possible to combine, say, two elements from column III of the periodic table with one element from column V to build an alloy whose band gap can be predicted: the band gap is partway between the band gaps of single, binary alloys made out of one of the column-III elements and the element from column V [*see illustration on next page*].

Light detectors for photonic communications also rely on transitions across the band gap, but the transitions are in reverse. When a photon impinges on a semiconductor, it excites an electron and creates a hole, provided its energy is greater than the energy across the band gap. If a voltage is applied across the semiconductor, the electrons and holes move in opposite directions and give a current that can be amplified and recorded. The detector can be built out of a uniform semiconductor, but if a *p-n* junction is incorporated, the built-in electric field around the junction helps force the excited electrons and holes to move toward the external circuit. In the devices known as avalanche photodiodes the electrons and holes moving in a high electric field generate more electrons and holes; the detected electrical signal is thereby increased.

Not only do the minimum optical losses of fibers determine the choice of material in lasers, diodes and photodetectors; the structure of the devices, particularly the lasers, also determines how the material must be made. Semiconductor lasers have become remarkably complex structures. The materials from which they are built have many thin layers of different composition and doping, which have different electronic and optical properties. The layers must often be separated by sharp boundaries and their thickness must be accurately controlled.

Furthermore, the layers have to be grown, or laid down sequentially, in such a way that the layering does not introduce defects that would degrade the electrical or optical performance of a device. Traditionally this requirement has been met by ensuring that atoms in successive layers are deposited epitaxially; that is, they are to fit into a single crystalline pattern that continues without disruption or distortion across the interfaces between the layers. The need for such crystalline perfection throughout the layered material severely limits the semiconductor alloys that can be sandwiched together. Materials must be chosen whose lattice constants, or units of lattice repetition, are closely matched. Although new techniques suggest that the need for epitaxial growth might one day be relaxed, it is still the guiding principle for building functional materials of highly complex structure.

One can begin to appreciate the need for complex structure by again considering the *p-n* junction. The electrons and holes injected into the region near the junction by an applied voltage are also free to leave the junction. Hence if the electrons and holes were not somehow confined, the number of pairs that recombine to yield light would be small compared with the total number injected. To trap the electrons and holes near the junction, the band gap in the junction region is made smaller than it is in the neighboring material. The particles are trapped because the energy levels they occupy in the junction region lie in the forbidden band gaps of the neighboring material; the particles cannot leave the region without changing their energy.

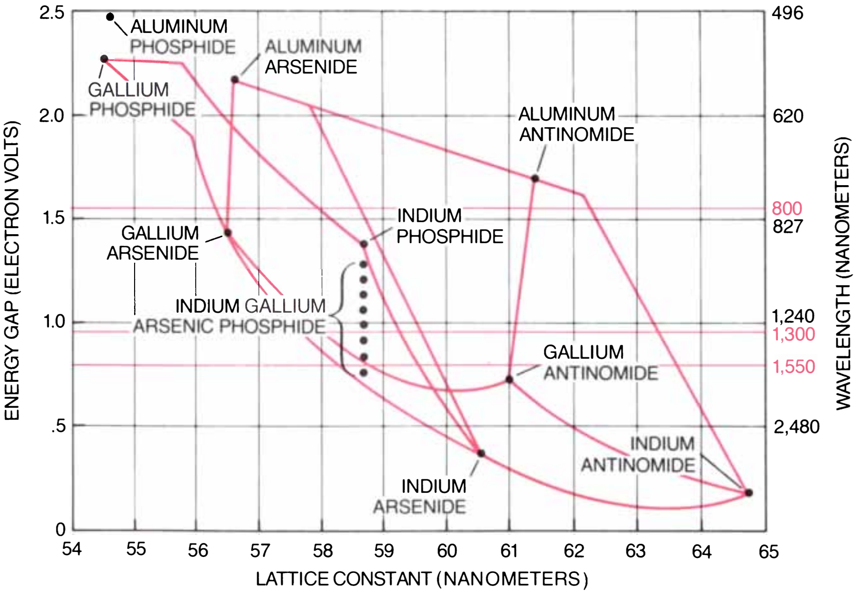
To increase the useful light emitted by a laser or a diode it is also essential to confine the photons once they are generated by recombination. The strategy here is the same as it is in building an optical fiber: if the refractive index of the junction region is higher than it is in the surrounding regions, emitted light that would otherwise pass out of the junction region is reflected back into it. By confining the electrons, the holes and the photons to the junction region and by placing mirrors of high quality at the ends of the region it is possible to stimulate recombinations faster than the photons can leak away at random. The light emissions become coherent and the device begins to function as a laser [*see illustration on page 152*]. In this way the first semiconductor heterojunction lasers to operate continuously at room temperature were built at Bell Laboratories in Murray Hill, N.J., and at laboratories in the U.S.S.R. at about the same time.

How can the complex, epitaxial and precisely doped materials needed for such a device be fabricated? To grow a layer of, say, gallium aluminum arsenide on a gallium arsenide substrate, the substrate is placed in an environment where gallium, aluminum and arsenic atoms arrive on its surface with a frequency that determines the composition of the alloy. If the temperature of the substrate is properly adjusted, the incoming atoms stick to the substrate at the correct crystalline positions. Atoms arriving later at the surface stick to the ones already deposited, again at the correct crystalline positions. The thickness of the new layer is determined by the flux of arriving atoms and the time allowed for growth.

The environment in which the crystal grows can be a liquid, a vapor or a high vacuum. In liquid-phase epitaxy the material to be deposited as the next layer is dissolved in solution, and the solution is cooled until it becomes supersaturated. The substrate is then immersed in the solution and exposed to the dissolved material at a controlled temperature. The dissolved material precipitates out of the solution and onto the surface of the substrate.

In vapor-phase epitaxy the substrate is put in a tube, which is set in a furnace. The material to be deposited streams into the tube as a gas mixture containing volatile compounds. The compounds decompose in the furnace and are either deposited on cooler surfaces or are carried out with the gas stream. If a change in doping or band gap is needed, the compounds in the gas stream are changed after an appropriate time. The sharpness of the interface between two layers depends on how quickly the composition of the vapor at the growing surface of the crystal itself can be made to change. That rate of change depends in turn on the design of the gas manifold that introduces the vapors, the gas flow within the growth tube and the precise way vapors arrive at and depart from the crystal surface.

The gases employed in vapor-phase epitaxy are extremely dangerous to health, and so costly measures must be adopted to ensure their safe use. There are two recent variations of the process that seem to offer advantages. In organometallic chemical-vapor deposition the required elements are introduced into the growth tube as compounds bound to organic substances. In that form they are comparatively harmless. The organic radicals of the molecules are released chemically as the elements that make up the semiconductors are safely deposited on the substrate. The second variation on vapor-phase epitaxy is called vapor-levitation epitaxy. Here the gases and volatile compounds are similar to the ones used in vapor-phase epitaxy, but the substrate, instead of resting in the vapor stream, is levitated by it.



BAND-GAP ENGINEERING of a semiconductor can be done by varying the elemental components of the semiconductor alloy in a controlled way. Here the energy across the band gap is plotted against the lattice constant, or the dimension of the basic unit of the crystalline lattice. The lines that connect points on the graph show how the band gap and the lattice constant vary for mixtures of the binary compounds to which the points correspond. Such mixtures are ternary compounds. For example, the ternary compound gallium aluminum arsenide can be made to have any band gap between about 1.4 and 2.2 electron volts by varying the ratio of gallium to aluminum between the band-gap extremes represented by gallium arsenide and aluminum arsenide. Materials of differing composition that have roughly the same lattice constant, such as these two binary compounds, can be deposited in alternating layers to create a single crystal lattice. Operating wavelengths for three important optical communications systems are labeled in color.

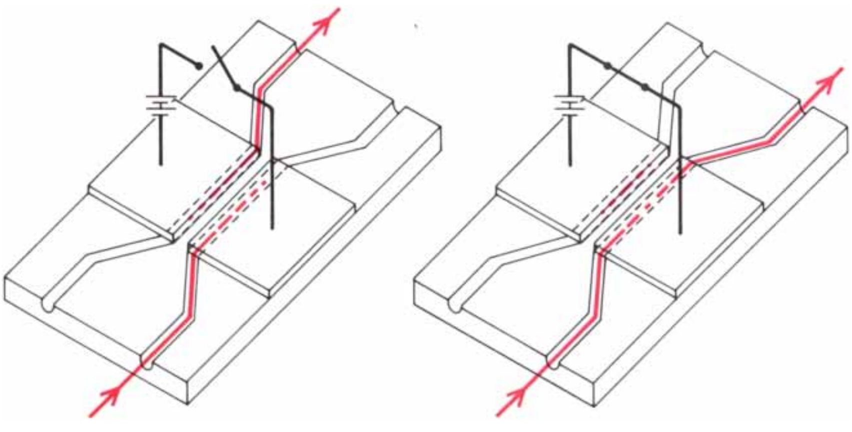
A third major method for growing complex semiconductor materials is called molecular-beam epitaxy. Semiconductor and dopant materials to be deposited on the substrate are put in an oven and heated, usually above their melting point, in a vacuum. The atoms evaporate from the surface of the heated material and travel in straight lines through the vacuum until they stick to the surface of the substrate or to the walls of the vacuum chamber. Shutters between each source and the substrate control the mixing of the deposit; the flux of each element toward the substrate can also be regulated by raising or lowering the oven temperature. Both processes are often controlled by computer. The ongoing growth of the material can be monitored by electron scattering from the surface. Structures of remarkable complexity can be built up.

None of these techniques has yet emerged as the dominant one. Liquid-phase epitaxy has been a workhorse in growing semiconductors for lasers and light-emitting diodes. It is simple in operation and relatively fast, but it cannot grow the very thin, sharply defined layers that are needed for the most modern devices.

It may turn out that chemical-vapor epitaxy, particularly with organometallic compounds, will become the methods of commercial choice. The growth of the crystal is still quite rapid, and it can take place over substrates that have a large area. The basic problem with the two methods is that they are done near a pressure of one atmosphere. Electron beams are scattered by the gas in the chamber; hence such beams cannot be used as they are in molecular-beam epitaxy to monitor the growth of a material. Furthermore, there appear to be fundamental limits to the precision of deposition that can be attained. The vapor flow can be turbulent, gases intended to give a sharp boundary between two growth layers can mix in the chamber and there is uncertainty about the composition of the stagnant gas layers close to the surface of the substrate. Such potential limits, however, seem not yet to have been reached.

Because molecular-beam epitaxy takes place in a vacuum, the process can deposit extremely thin layers with sharply defined interfaces. Its disadvantages are that the growth rate is quite slow, the deposition can vary across the substrate because of the geometric arrangement of the source ovens and the initial capital costs are high. Its versatility, however, makes it the choice of many scientists, if not yet of manufacturers.

The clear distinctions among the growth techniques have recently begun to fade, and new techniques have appeared. For example, organometallic chemical-vapor epitaxy can now be carried out at a pressure of only about one one-thousandth of an atmosphere. A more radical change is to deposit vapor and organometallic compounds by molecular-beam epitaxy. The hybrid process retains all the advantages of the vacuum, but the growth rates are higher than they are in conventional molecular-beam epitaxy and the source materials are easier to change.



ELECTRO-OPTICAL SWITCH can direct the flow of light on a crystal of lithium niobate. The light is confined to waveguides in the crystal, defined by a surrounding material of lower refractive index. In the absence of an applied voltage (*left*) light propagating through the lower waveguide interacts with the upper guide, and the light transfers into the upper guide. If the proper voltage is applied, light remains in the lower guide (*right*).

The perfection of the techniques of fabrication described above was driven largely by the need to create complex heterojunction lasers. Such techniques have now opened the way to what has been called band-gap, or atomic, engineering. What kinds of physical feature do they enable the engineer to control?

In general, individual atomic layers of a material are not manipulated one by one, although that is clearly the ultimate aim. Properties are commonly varied, however, over only a few atomic layers. For example, the change in band gap, which largely determines the optical properties of a material, and the doping of impurities, which give rise to its electrical properties, can be controlled independently. Moreover, the composition of a semiconductor can be changed continuously, say from gallium arsenide to gallium aluminum arsenide, and so the band gap can be made to vary smoothly over any predetermined distance. If the composition is made to alternate abruptly many times over, a series of potential barriers and wells are built up, with periods as small as one nanometer across. Such a structure is called a superlattice.

Electrons introduced into a superlattice by doping can move only in the plane of the layers because the larger band gaps in the neighboring layers create an energy barrier. Furthermore, the energy of the electrons in the transverse direction is quantized, and so their energy levels and the wavelength of the light they emit through recombination are changed by the layering. In this context superlattices are called multi-quantum-well materials. It is also possible to dope the layers in such a way that the dopant atoms are in the barrier layers and the free electrons or the free holes migrate to the neighboring layers. This procedure eliminates the scattering of the charge carriers by the impurities, and so it increases the carrier mobility; it is known as modulation doping.

The most recent study of fabrication technique suggests, as mentioned above, that materials need not have the same lattice constant in order to be grown successfully in alternating layers. For example, it has now been demonstrated that gallium arsenide can be grown on silicon; a layered material made of these two kinds of semiconductor should combine the photonic utility of a widely used III-V semiconductor with the well-known advantages of silicon in electronics. A superlattice can be made out of two materials with a different lattice constant as long as the individual layers are thin and the difference between the two lattice constants is not too great. A mutual strain between the atoms in the layers gives rise to a new perfect crystal with properties unlike those of either of its constituents. Such a material is called a strained-layer superlattice.

One of the most important potential applications of the solid-state superlattice is as an active element in a photonic circuit. An active circuit element does not merely transmit light passively; it also interacts with light by generating, modulating or switching it. An active circuit element can thereby signal its state to the rest of the circuit. The dream of building an all-photonic computer depends on the development of such devices.

In the laboratory investigators have shown that certain III-V semiconductor superlattices, as well as several other materials, exhibit a nonlinear response to an optical signal. A small increase in the incident light intensity on the material can cause a sudden, large increase in the intensity of the output [*see upper illustration on next page*]. Simple photonic information processing has been carried out that exploits this effect [*see lower illustration on next page*]. It is by no means clear, however, that III-V materials are the best that exist, or the best that can be created, for photonic switching.

It must be admitted, however, that photonic switching and other major requirements of photonic computation have been rather slow to develop. The only commercially available switch is a device made from lithium niobate ($LiNbO_3$) that changes the path of a light signal. The device depends on the changes made in the optical properties of lithium niobate that are brought about by an applied electric field. The material is a crystalline oxide made by melting highly pure powders of niobium pentox-

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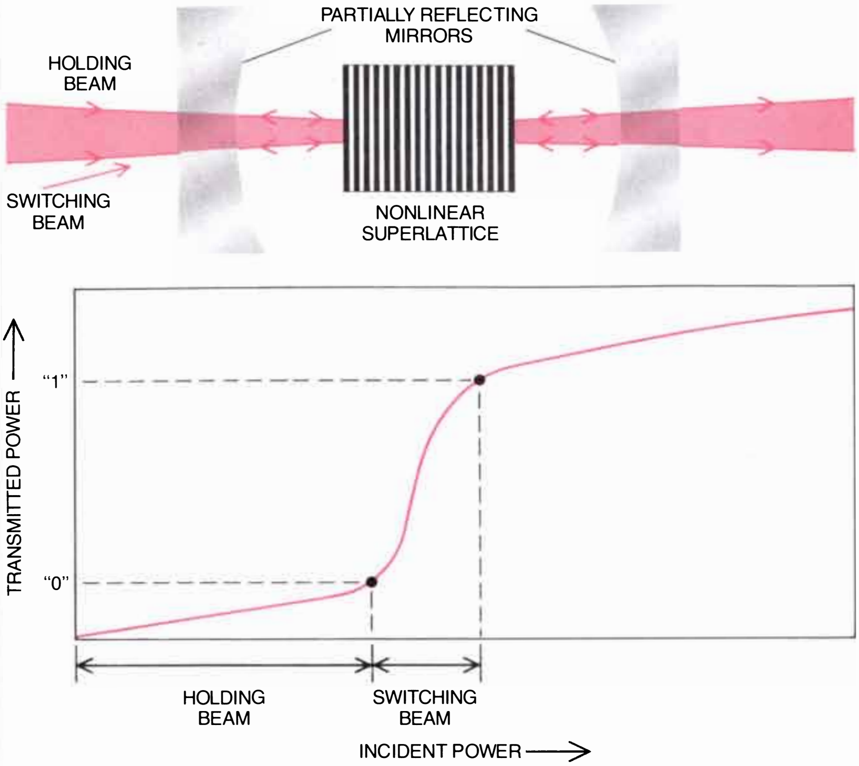
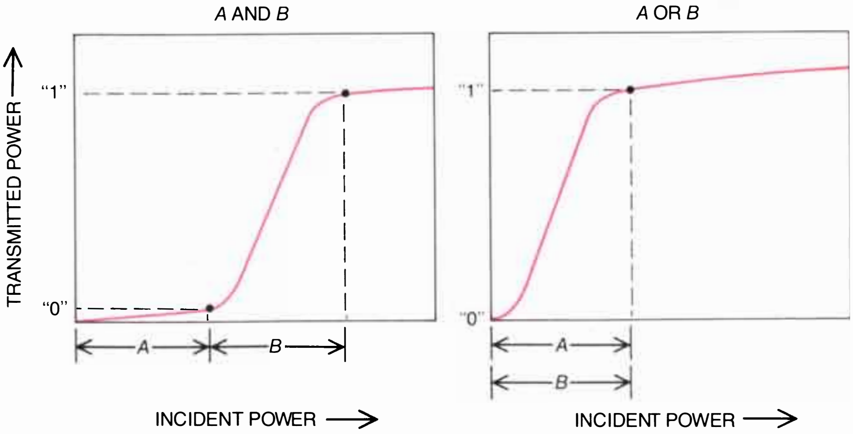
ide (Nb_2O_5) and lithium carbonate ($LiCO_3$) in a platinum crucible at a temperature of more than 1,250 degrees Celsius. A small seed crystal is then dipped into the melt and slowly withdrawn; in this way a single crystal of lithium niobate as large as three inches in diameter can be grown on the seed. To align the optical properties of the crystal it is cooled in an electric field, then sliced and polished.

To make a switch out of lithium niobate two waveguides, or optical paths, are defined on the surface of the crys-



PHOTONIC TRANSISTOR can be constructed out of a crystal of nonlinear optical material and a pair of partially reflecting mirrors. The light transmitted by a nonlinear optical material is not proportional to the power of the incident beam. Here the material is a superlattice: a material constructed by depositing alternate layers of two different alloys. Light passes through the mirror at the left, enters the superlattice crystal and is partially reflected by the mirror at the right; the transmission power of the device is plotted for values of the power of the incident beam. The power of a holding beam is adjusted so that it is just below the threshold for a rapid increase in transmitted power. If a small switching beam is added to the holding beam, it pushes the incident power just over the threshold. Thus the device effectively amplifies the light in the switching beam.



LOGIC GATES can be made from a photonic transistor. For the *and* gate (*left*) the power of the incident light pulses is adjusted so that the power threshold of the superlattice is crossed only if both pulses are turned on. For the *or* gate (*right*) the power threshold is adjusted so that it is crossed if either one (or both) of the incident pulses is turned on.

tal. A thin film of titanium is deposited photolithographically through a template to make the desired waveguide pattern on the crystal. The titanium is then fused with the lithium niobate crystal just below the surface deposit by heating it to about 1,000 degrees C. The remaining titanium is then etched away to leave an optical path of titanium-doped material in the lithium niobate substrate. Light is confined to the crystal by the same mechanism that confines it to the core of an optical fiber: the refractive index of the titanium-doped waveguide is higher than that of the surrounding lithium niobate. Two waveguides are defined close to each other along a surface, with electrical contacts next to each one. If an electric field is applied across the guides, it changes their refractive index and causes light from one guide to switch into the other one [*see illustration on page 155*].

It should be clear by now that although electro-optic technology is well established, a truly photonic technology is only beginning to emerge. One basic requirement of a more mature technology is the integration of the photonic devices. At present such devices are discrete and must be connected individually. If one can extrapolate the development of photonic integration by analogy with the integration of discrete electronic components, the process will proceed in two steps. First, optical devices will be integrated with their associated electronics; this step is already under way. Second, optical integrated circuits may be built that will require no electronics at all.

One can reasonably expect further changes in the devices and transmission mediums, in the materials that comprise them and in the ways such materials are made. A considerable increase in yield and reliability of these materials and a decrease in the cost of devices made of III-V semiconductors should be expected. As the various techniques of crystal growth are applied to nonlinear materials or to organic materials, it is likely that entirely new properties will become available to the designer of photonic circuits.

In the past decade photonics has undergone revolutionary development, and this has demanded a revolution in the way glasses, III-V semiconductors and nonlinear materials are designed and fabricated. Although one cannot predict the future changes with any confidence, there is every indication that as the technology becomes widespread and progressively cost-effective, it will stimulate equally radical changes in the requirements for future photonic materials.

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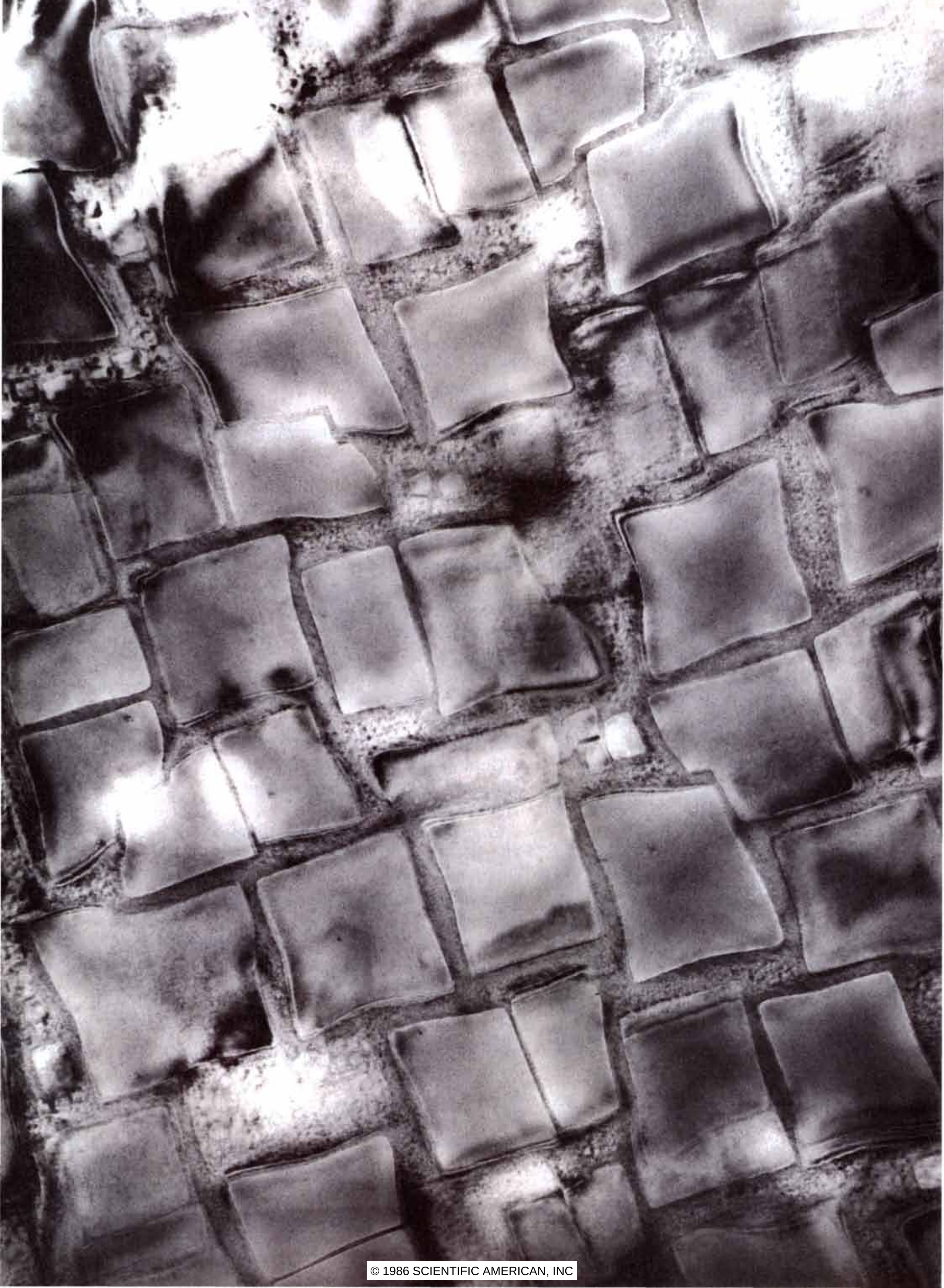


Advanced Metals

With the aid of new processing techniques, metallurgists create and exploit irregularities in the metallic crystalline structure to make exceptionally strong alloys that resist heat and corrosion

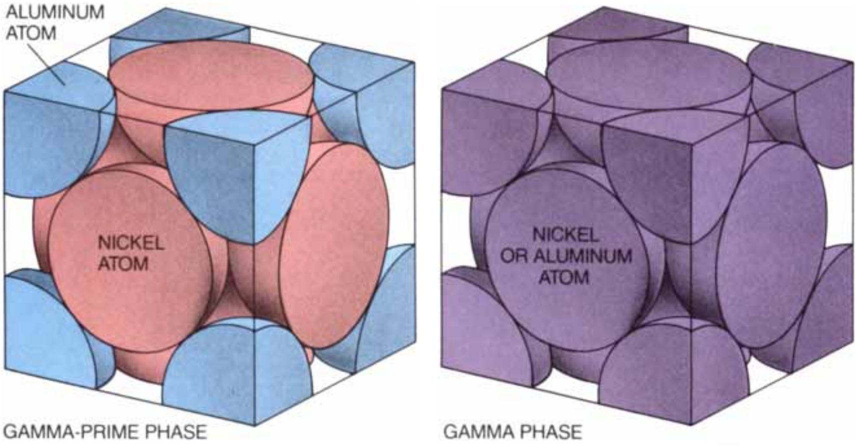
by Bernard H. Kear

Metals may be brittle or workable, hard or soft, easy to melt or able to withstand extremely high temperatures. Almost paradoxically, a metal's properties can often be enhanced by exposing it to various stresses: working a metal can make it harder; exposing it to the right degree of heat can make it less likely to lose its strength at high temperatures. The key to these properties lies in the crystalline structure that underlies the form of all metals.

The atoms in a metal are packed together tightly, like marbles in a box. Like such a collection of marbles, the atoms tend to form planes that are stacked together closely. The ways in which the planes fit together determine many of the mechanical properties of a given metal. Alloying a metal—adding atoms of some other metal—changes the way the planes of atoms fit together, often increasing the strength of the product. Thus bronze is stronger than either copper or tin, its two constituent metals.

In the 1930's investigators began to realize that the pure, perfect crystalline lattice of metals could not account for all their observed properties. Indeed, it is now apparent that defects in the lattice—places where the planes of atoms do not stack together to fit perfectly—usually play the dominant role in determining such properties as a metal's ductility, brittleness and behavior at high temperatures. In recent years metallurgists have taken advantage of this knowledge to develop a new generation of advanced metal alloys. To create advanced metals, materials scientists have deliberately manipulated the complex structure of flaws and inhomogeneities within the metallic crystalline lattice.

Advanced metals represent a major turning point in metallurgy. In the past the metallurgist relied largely on trial and error to gauge what combination of ingredients and processing steps would produce the best alloys. It is now possible to custom-design alloys, by means of techniques based on a deep knowledge of underlying microstructure and micromechanics.



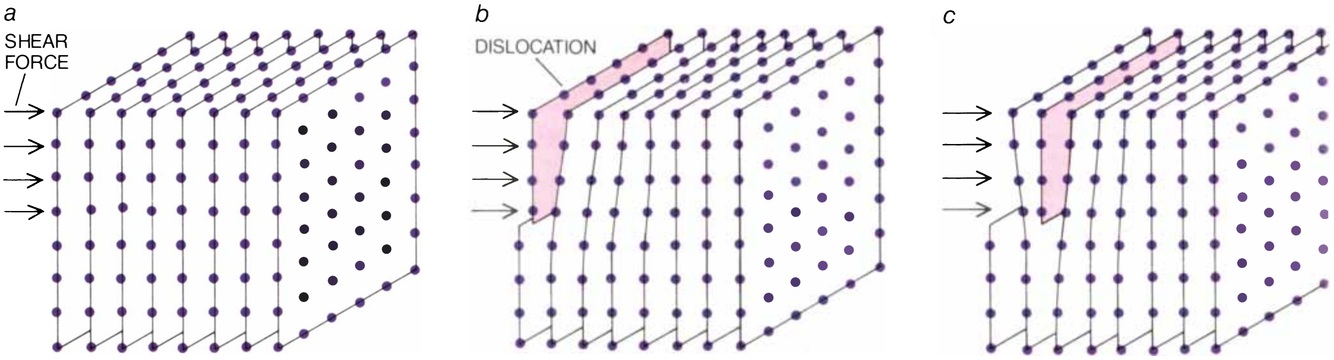
NICKEL-ALUMINUM SUPERALLOY derives its strength from an assemblage of crystals of one phase, or crystalline structure, embedded in a matrix of a different phase. The cubelike crystals seen in the electron micrograph on the opposite page are made of the gamma-prime phase of nickel-aluminum. They are built up of "unit cells" having an ordered face-centered cubic structure (*above left*) in which atoms of aluminum and nickel occupy specific sites in the crystal lattice. The surrounding matrix is made of the gamma phase (*above right*), which also has a face-centered cubic structure but is unordered: atoms of either element may occupy any site. The ordered structure of the gamma-prime cuboids is highly resistant to deformation, and it hardens the superalloy. The composition of the superalloy shown here is approximately three parts nickel to one part aluminum. The sample is magnified about 140,000 diameters in the micrograph, which was made by David Pearson in the materials laboratory of the United Technologies Research Center.

Many of the advanced metals currently in use were developed with a single application in mind: the aircraft gas-turbine, or turbojet, engine. The components in a gas-turbine engine are exposed to extreme conditions of every kind: high temperatures, corrosive gases, vibration and high mechanical loads due to centrifugal forces. They are also exposed to a subtler stress. An engine is started, accelerated, decelerated and stopped every time the airplane it propels takes off and lands. The repetition of this cycle can lead to a kind of failure known as low-cycle fatigue, in much the same way that bending a wire back and forth repeatedly can cause it to break because of "metal fatigue."

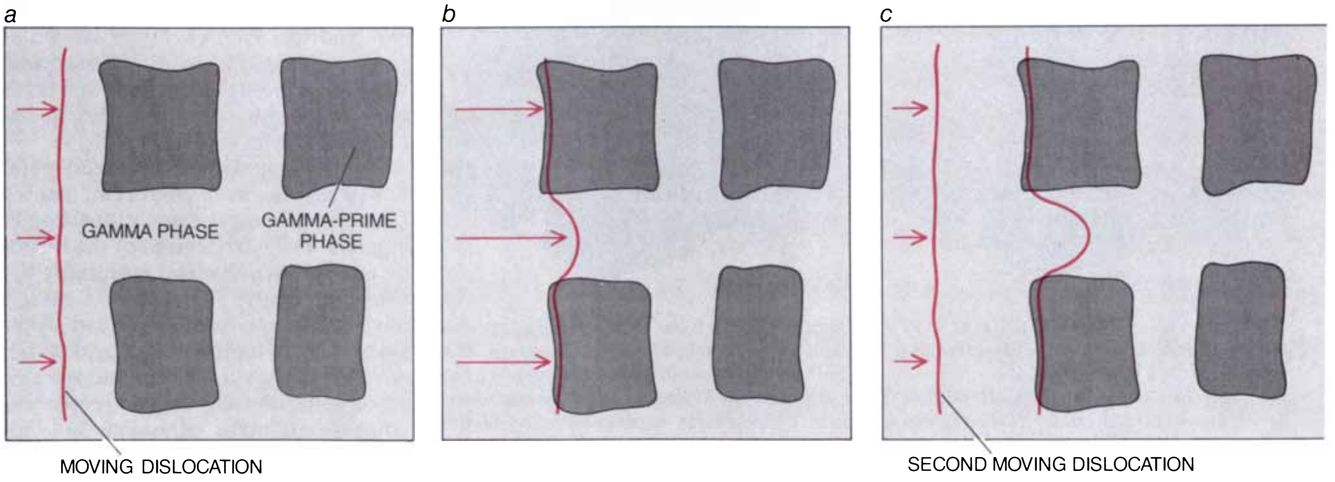
The development of advanced metal alloys has been an important pacing factor in the improvement of turbojet engines. The basic design of the turbojet engine has remained essentially the same for nearly 30 years. As metals have been produced that can withstand higher temperatures and greater stresses, they have been incorporated directly into the engines, replacing components made of less suitable alloys and thereby increasing performance and reliability. It is natural, in discussing advanced metals, to base the discussion on the applications for which the metals have been developed. Because the construction of turbojet engines has been one of the main driving forces in the development of advanced metals, and because the gas-turbine engine presents almost every kind of severe condition likely to be encountered by an advanced metal, I shall discuss advanced metals in the context of the modern aircraft gas-turbine engine.

A typical turbojet engine consists of three main sections called the compressor, the combustion chamber and the turbine [*see illustration on page 162*]. The compressor consists of a series of rotating disks, each disk bearing a set of fanlike blades. The disks alternate with large rings of stationary blades called stators or vanes, which are attached to the engine casing and redirect the flow of air as it passes from one set of rotating blades to the next. The compressor pulls air into the engine, raises its temperature and pressure and delivers it to the combustion chamber. In the combustion chamber the high-pressure air is thoroughly mixed with a fine spray of fuel and the mixture is ignited. The hot exhaust gases expand rapidly. They pass at high speed through the turbine, an array of moving and stationary blades much like those in the compressor, and are expelled through the exhaust nozzle. It is the high speed with which the exhaust gas leaves the rear of the engine that pushes the aircraft forward. As the exhaust gases pass through the turbine they spin it; the spinning turbine is connected to shafts that drive the compressor, drawing in more air.

The components in the various sections of the engine have different structural requirements. The blades and vanes in the compressor must be able to withstand aerodynamic loads, and the rotating blades must also resist "creep," the tendency to elongate gradually because of centrifugal force. The disks that carry the rotating blades must have a high load-bearing capacity in order to hold the blades against centrifugal forces. Most components in the combustion chamber, which is more intricately constructed than either the compressor or the turbine, must be formable and weldable, and they must resist thermal fatigue (failure due to repeated constrained expansion and contraction during cycles of high and low temperature), corrosion and distortion at high temperatures. Alloys in the combustion chamber need not be particularly strong, but they must maintain their strength at temperatures as high as 1,100 degrees



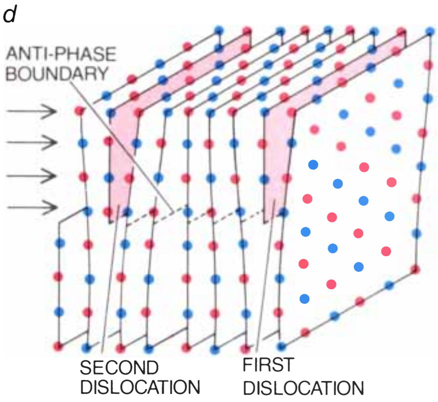
DEFORMATION of a metal crystal creates a defect called a dislocation in the crystal's microstructure. When a shear force is applied to the crystal (*a*), half of the outermost plane of atoms is pushed into the material (*b*) until it pushes against the next half plane in. That half plane eventually breaks off, allowing the first one to take its place (*c*). The extra half plane in the crystal structure is called a dislocation. If the shear force is sustained, the dislocation will continue to move through the material by the same process of breaking off and replacing half planes of atoms. Metals in which dislocations do not move easily are more difficult to deform: they are harder metals. In an ordered crystal, in which specific positions are occupied by atoms of particular elements (*d*), a single dislocation may disturb the order of the crystal; it is therefore difficult for a dislocation to move through an ordered



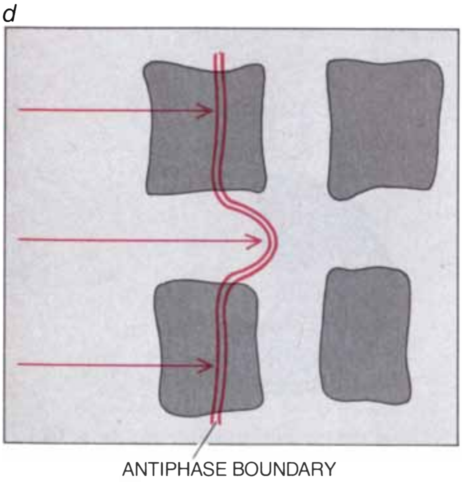
STRENGTH of nickel-based superalloys derives from the difficulty with which single dislocations move through cuboids of the gamma-prime phase. A dislocation (*color*) moves relatively easily through the unordered gamma material of the superalloy (*a*). Because the gamma-prime phase is ordered, however, a single dislocation cannot move through it easily, and so the cuboids of gamma-prime in the matrix pin moving dislocations in place (*b*), making the metal more difficult to deform. When a second moving

Celsius. Components in the turbine have essentially the same requirements as those in the compressor, but they must also be able to withstand corrosive gases and far higher temperatures than are encountered in the compressor. Components throughout the engine must have very stable microstructures, in order to maintain their properties over long periods.

The alloys best suited to many of the extreme conditions for which advanced metals have been developed are the nickel-based materials known as superalloys. In a conventional alloy all the atoms are aligned according to one particular crystalline structure; that is, all the planes of atoms fit together in the same way. Usually a sample consists of many grains, or individual crystals, bonded together. The crystal structures of different grains are not aligned with one another, but within each grain the atoms fall into the same kind of crystalline alignment as the atoms in any other grain.



crystal. A second dislocation restores the crystal's order, and so dislocations move through ordered crystals in pairs. The region between the dislocations, called an antiphase boundary, has higher energy than the rest of the crystal, and so it takes extra energy to deform ordered crystals.



dislocation (*c*) joins the first one, the two can move together through the gamma-prime cuboids, with a small, high-energy antiphase boundary between them (*d*).

The atoms in a superalloy, on the other hand, fall into two or more distinct phases, or types of alignment. In nickel-based superalloys the phases are called gamma and gamma-prime. Small, usually cubical crystals of the gamma-prime phase are embedded in a matrix made up of the gamma phase. The principal difference between the two phases is that the atoms in the gamma-prime phase are more highly ordered than those in the gamma phase. That is to say, the planes of atoms fit together in the same way in both phases, but in the gamma-prime phase specific sites in each plane must be occupied by nickel atoms and other specific sites must be occupied by atoms of the alloying metal, which is usually aluminum. (In gamma-prime nickel-aluminum there are three nickel atoms for every atom of aluminum.) In the gamma phase any kind of atom may occupy any site.

To understand the special properties of superalloys it is first necessary to understand how the microstructure of a metal normally responds to stresses. Suppose a shear force is applied to a metal sample; that is, suppose the section of the sample above some imaginary plane called the shear plane is pushed to the right, while the section below the shear plane is held in place.

What is the effect of such a force on the microstructure of the metal? Imagine planes of atoms on each side of the sample that are roughly perpendicular to the applied forces and hence also roughly perpendicular to the shear plane. The half of the leftmost plane that is above the shear plane will be pushed to the right but the half that is below the shear plane will not. The plane will therefore break in two, if the force is strong enough, and the top half of the plane will be pushed a little way into the sample. Eventually it will be pushed far enough into the sample to push against the half plane of atoms it is stacked next to: the half plane just inside the sample. As a matter of fact, it will actually displace that half plane, pushing it farther into the sample and taking its place in the orderly crystal. The displaced half plane will in turn displace the next half plane in, taking its place.

In this way an extra half plane will propagate through the sample, and eventually the top of the sample will have moved to the right by the thickness of one atomic plane. If the force is maintained, the sample will continue to deform in this way. The extra half plane that moves through the sample is known as a line dislocation.

A metal in which it is difficult for dislocations to move is not as easy to deform as one in which dislocations can move freely: it is a harder metal. The microstructure of nickel-based superalloys makes it difficult for dislocations to move, and so the superalloys are harder than most ordinary alloys.

The key to the hardness of nickel-based superalloys is the presence of crystals of the gamma-prime phase. The gamma-prime phase is ordered: atoms of nickel and aluminum must occupy specific positions within the crystal lattice. When one half plane is shifted over to replace an adjacent half plane, certain sites that in the original half plane were occupied by aluminum atoms come to be occupied by nickel atoms, and vice versa. This arrangement of atoms has higher energy than the undeformed gamma-prime phase, and so it is difficult for a dislocation to propagate through a gamma-prime crystal. (Dislocations move through the gamma-prime phase in pairs, with the second dislocation to pass through the material undoing the disordering caused by the first one.)

In a sample of a superalloy containing both phases, dislocations move relatively easily through the material in the gamma phase but are pinned down and held in place by the crystals of gamma-prime. The superalloy therefore resists deformation and is harder than a conventional alloy.

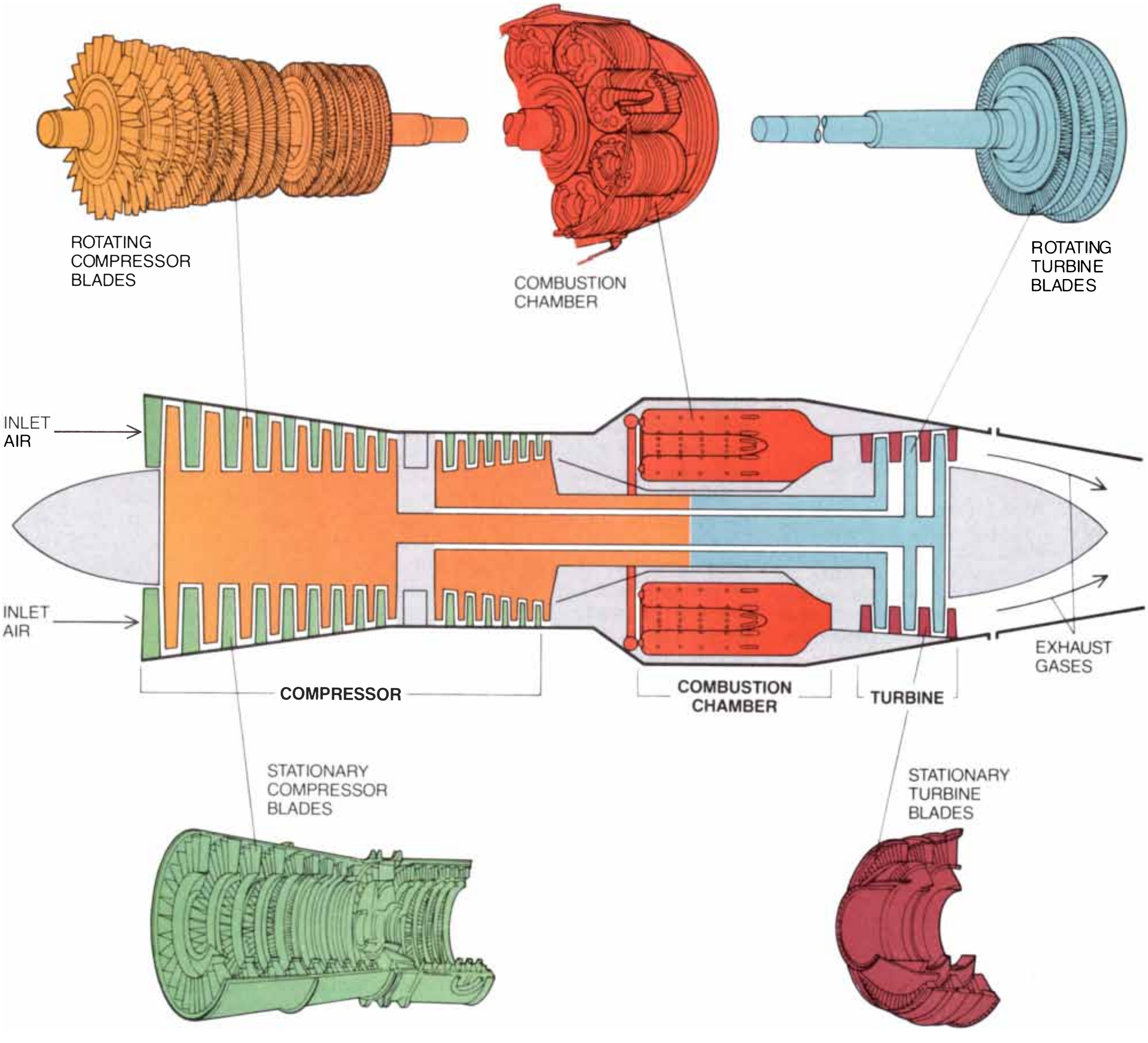
To make a superalloy a piece of nickel is melted and mixed with aluminum. Usually a small amount of chromium is added in order to protect the final product from corrosion, and small amounts of other metals such as titanium and tungsten are also added for additional hardening. Then the mixture is cooled. The freezing point of the gamma phase is higher than that of the gamma-prime phase, and so as the mixture is cooled it forms a mass of gamma-phase nickel-aluminum. As the alloy is cooled further in the solid state, small cuboids of gamma-prime begin to form within the surrounding matrix of gamma.

The ultimate size of the gamma-prime particles can be controlled by varying the rate at which the material is cooled. Superalloy engine components are strongest when they contain a high proportion (about 60 percent by volume) of very small gamma-prime crystals. When the components are exposed to high temperatures during the engine's operation, however, the small gamma-prime crystals tend to grow larger. Some complex heat treatments have been devised in order to achieve certain specific high-temperature mechanical properties and to ensure that components with those properties will perform consistently over many cycles of use. A typical procedure involves subjecting the alloy to a relatively high temperature, cooling it rapidly and then aging it at a lower temperature to achieve the desired size and distribution of gamma-prime crystals.

In the past few years a variation on the nickel-aluminum superalloys has excited a great deal of interest among metallurgists. It has been known for some time that the strength of pure gamma-prime nickel aluminide increases radically with temperature. The effect has intrigued investigators for decades, but attempts to exploit it have been frustrated by another property of gamma-prime that is related to its hardness: it is very brittle.

When a sample of pure gamma-prime nickel aluminide is worked, the individual grains, or crystals, of gamma-prime that make up the sample remain hard, but they break apart from one another at the grain boundaries (the borders between grains) and the sample as a whole tends to crumble. In 1979 Kiyoshi Aoki and Osamu Izumi of Tohoku University discovered that adding a small amount of boron to the sample can prevent it from crumbling. The boron tends to gather at the grain boundaries and somehow makes it possible for the grains to slide past one another without breaking apart. The exact mechanism by which this happens is not known and is the subject of active research. As little as .02 percent by weight of boron can transform gamma-prime nickel aluminide from brittleness to ductility.

Nickel-based superalloys, particularly those with high proportions of gamma-prime content, generally become stronger at higher temperatures,



AIRCRAFT TURBOJET ENGINE, a primary application for advanced metals, exposes its metal components to nearly every kind of severe condition possible, including high temperature, centrifugal forces, vibration and low-cycle fatigue (a stress imposed by repeated cycles of start-up, acceleration, deceleration and shutoff). In the compressor a series of rotating disks bearing fanlike blades pull air into the engine, raising its temperature and pressure; stationary blades redirect the air between sets of rotors. In the combustion chamber the air is mixed with fuel and the mixture is ignited. Expanding exhaust gases pass through the turbine (an assembly like the compressor), spinning it. The turbine is connected to shafts that drive the compressor. The exhaust gases leave the engine at high speed; the difference between the velocity of the inlet air and that of the exhaust gases drives the engine forward.

peaking in strength at about 850 degrees C. Most advanced superalloys retain useful strength at temperatures as high as 1,000 degrees. In gas-turbine aircraft engines, heat-resistant nickel-based alloys make up the compressor blades in sections of the compressor where the air is at its highest temperatures and pressures (the sections nearest the combustion chamber). They also make up the turbine blades in the sections of the turbine that are closest to the combustion chamber, where the exhaust gases are hottest.

Nickel-based superalloys have limitations at very high temperatures, and so components in the combustion chamber itself, which can get as hot as 1,100 degrees, are usually made of cobalt-based alloys. Cobalt-based alloys are also used to make the stationary vanes in the sections of the turbine nearest the combustion chamber.

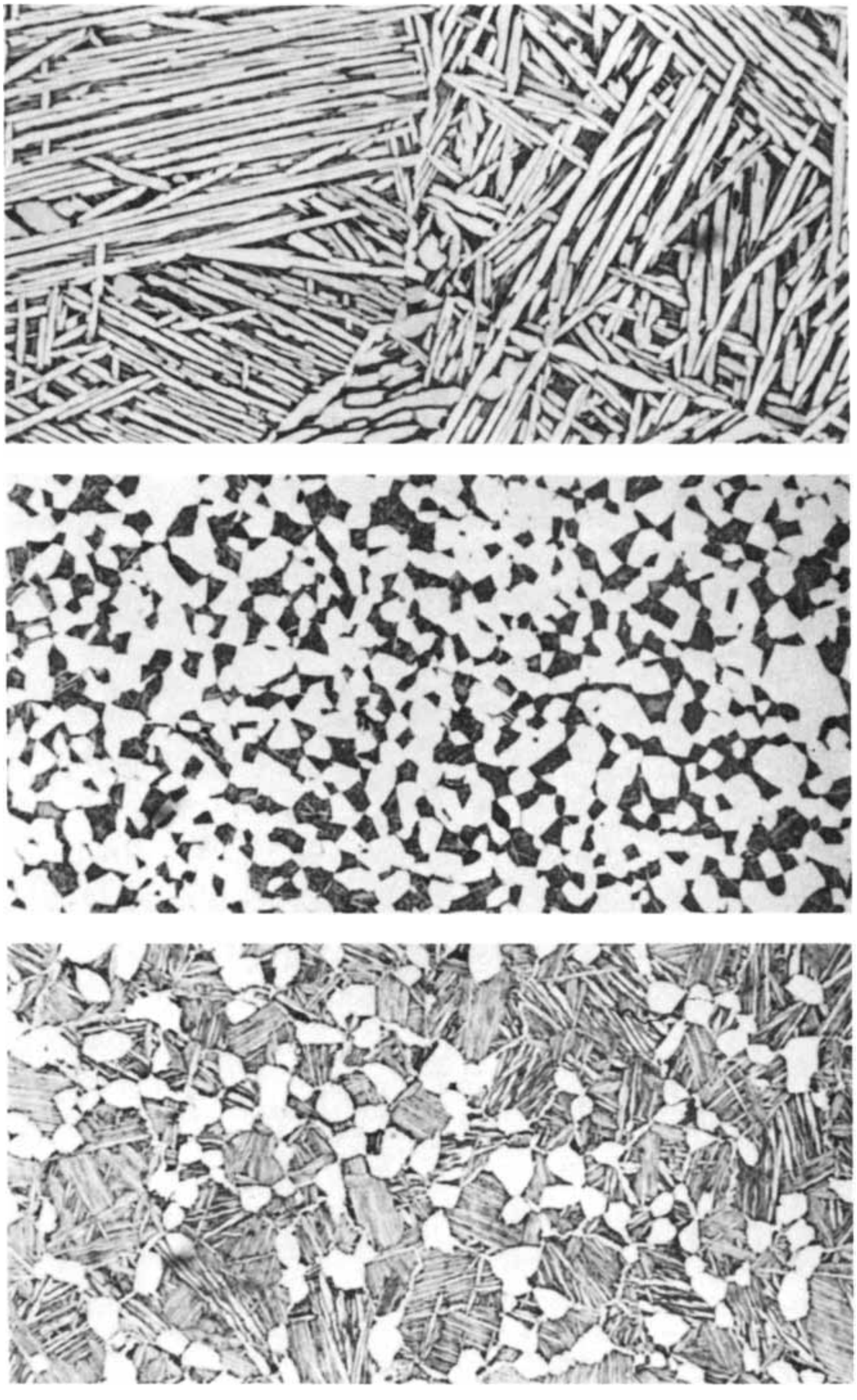
The cobalt-based alloys are not as strong as nickel-based superalloys, but they retain their strength up to much higher temperatures. They derive their strength largely from a distribution of refractory metal carbides (combinations of carbon and metals such as tungsten and molybdenum), which tend to collect at the grain boundaries between individual crystals of the alloy. This network of carbides strengthens the alloy and is stable all the way to the alloy's melting point.

In addition to refractory metals and metal carbides, cobalt alloys generally contain high levels of chromium to make them more resistant to the corrosion that normally takes place in the presence of hot exhaust gases. The chromium atoms join with oxygen atoms to form a protective scale of chromium oxide, which shields the alloy from the corrosive gases. Because cobalt-based alloys are not as hard as superalloys, they are easier to weld; superalloys are not very forgiving, and they can crack under thermal strain. Cobalt-based alloys are therefore more suitable for parts that need to be worked or welded, such as those in the intricate structures of the combustion chamber.

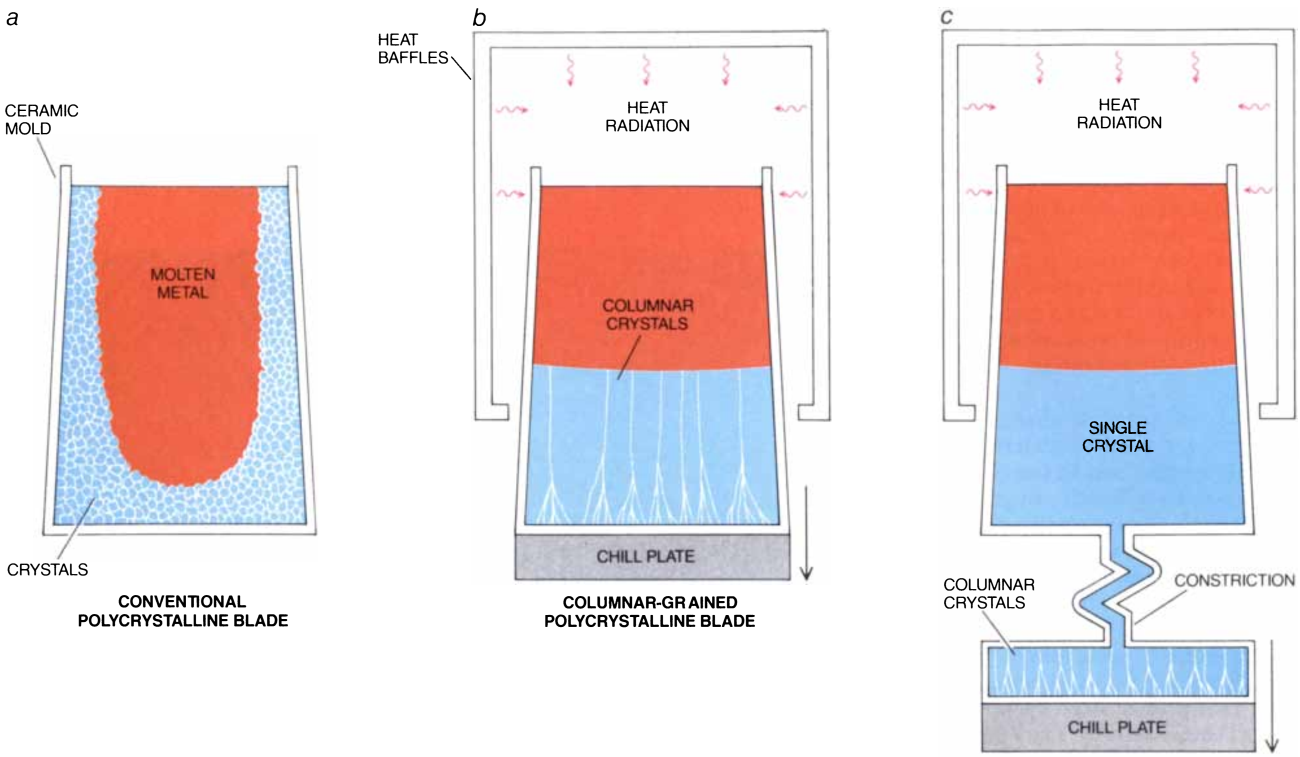
In some applications high strength and consistency at high temperatures are not as crucial, and the weight of each component becomes a greater consideration. In a gas-turbine engine this is the case for the blades and disks in the sections of the compressor nearest the air inlet, where temperatures and pressures are moderate. For these applications titanium-based alloys are often the most appropriate ones.

Like nickel-based superalloys, titanium-based alloys consist of two phases. They are the alpha phase, which forms at low temperatures, and the beta phase, which crystallizes earlier in the cooling process and forms the matrix in which the alpha-phase crystals reside. Alpha-phase crystals can have two basic shapes. Normally, when the alloy is produced by heat treatment and cooling, the alpha-phase crystals are lens-shaped. When the material is hot-worked and then heat-treated, the alpha-phase crystals are more spheroidal.

The lens-shaped structure is more creep-resistant (able to withstand the



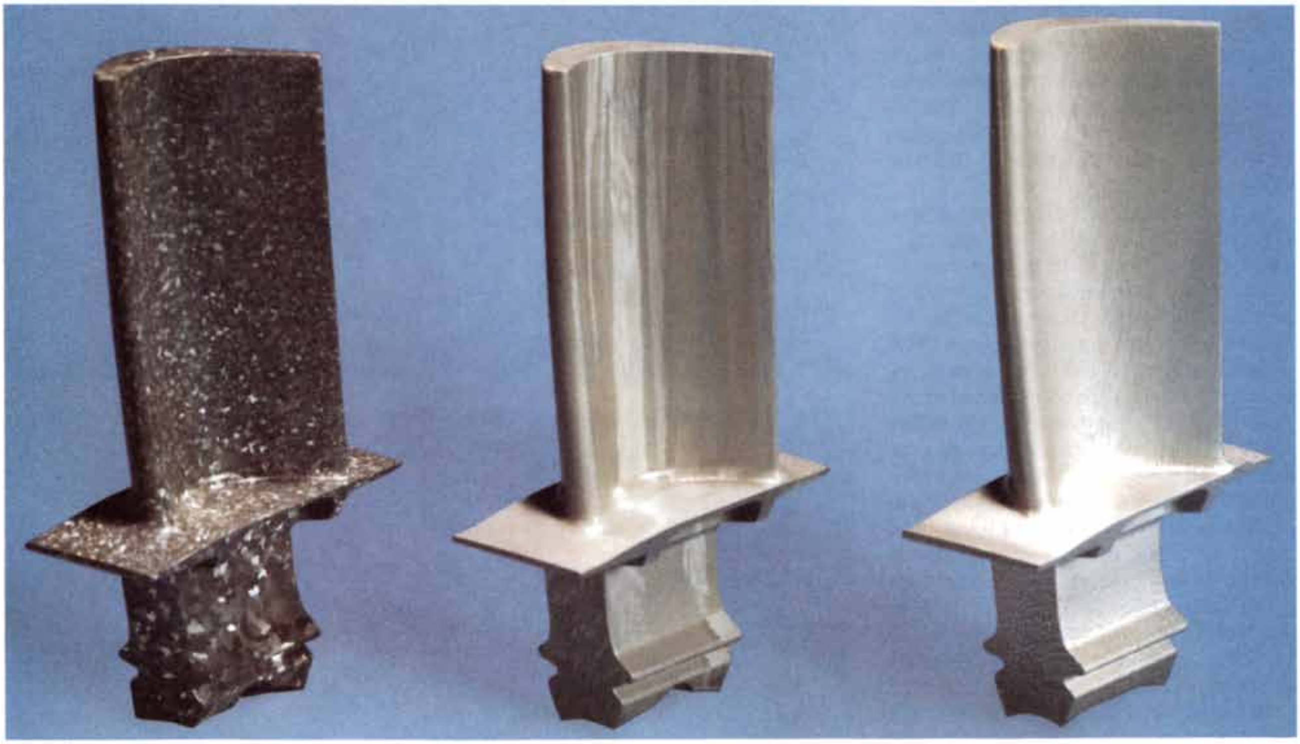
TITANIUM-BASED ALLOYS, like nickel-based superalloys, consist of crystals of one phase (*light*) buried within a matrix of another phase (*dark*). The two phases are called alpha and beta respectively. Crystals of the alpha phase can take on two forms: lens-shaped (*top*) and spheroidal (*middle*). Each conformation has useful properties, and so processing methods have been developed that will cause both types of alpha-phase crystal to form in the same sample (*bottom*). In these micrographs, made by Daniel Eylon of the University of Dayton and Francis H. Froes of the U.S. Air Force materials laboratory at Wright-Patterson Air Force Base, the titanium samples are magnified about 600 times.



CONVENTIONAL POLYCRYSTALLINE BLADE

COLUMNAR-GRAINED POLYCRYSTALLINE BLADE

SINGLE-CRYSTAL BLADE



DIRECTIONAL SOLIDIFICATION produces turbine blades that are resistant to "creep," the gradual elongation of the blade due to centrifugal force. In standard casting techniques (*a*) molten metal is poured into a ceramic mold and allowed to cool. The metal crystallizes in many places at once, and so the final result is a blade made of many crystals oriented randomly with respect to one another. In directional solidification (*b*) the mold is preheated and held in a system of heat baffles. The bottom of the mold is attached to a water-cooled copper chill plate. Molten metal is poured in and the mold is slowly lowered out of the hot zone. Crystals first form near the chill plate, and they grow upward in long columns. In such a blade the boundaries between individual crystals are parallel to the centrifugal forces acting on the blade, and so the crystals will not be pulled apart from one another by centrifugal force; the blade is therefore less likely to creep and crack under rotation. It is also possible to grow a blade that has no grain boundaries at all and is therefore even stronger (*c*). The same method of solidification is applied, but the mold has a corkscrew-shaped constriction, or bottleneck, partway up. As the mold is withdrawn from the hot zone, columnar crystals begin to grow, but only one of the crystals can fit through the bottleneck. Above the bottleneck that crystal expands to fill the entire mold, producing a turbine blade made of a single crystal. Grain structures of the three types of blade are apparent in photographs (*bottom*).

gradual lengthening that blades suffer when they are rotated at high speeds for long times) than the spheroidal structure, but it does not stand up as well to low-cycle fatigue. Since resistance to creep and to low-cycle fatigue are both important in rotating components, investigators have developed treatments that produce alpha-phase crystals with both shapes in the same sample of alloy.

Titanium-based alloys are far less dense than cobalt alloys and nickel-based superalloys, and so they have a higher ratio of strength to weight for temperatures below about 500 degrees C. In spite of many improvements in techniques for alloying, heat treatment and mechanical working, the maximum temperature at which titanium-based alloys are serviceable is still disappointingly low. Titanium alloys are weakened at absolute temperatures less than half their melting point, whereas superalloys maintain their strength to temperatures about seven- or eight-tenths their melting point.

Some promise for overcoming this temperature limitation is offered by the so-called titanium aluminide intermetallics TiAl and Ti_3Al. These alloys have lower densities, higher elastic stiffness and the capability to withstand higher temperatures than conventional titanium alloys. Intermetallics have already been exploited in the fabrication of compressor casings and turbine stator rings; a titanium aluminide stator ring is about 43 percent lighter than a ring made from a conventional nickel-based superalloy.

At least as important as the advanced alloys themselves are advanced techniques for processing metals. Advanced processing techniques enable metallurgists to exploit new microstructural knowledge to the fullest. They make it possible to shape and form samples of well-known alloys in ways that were never before possible, and to create advanced metals that could not have been made at all by older techniques.

One of the most important advanced processing techniques is called directional solidification. The concept of directional solidification can be traced to pioneering work done in 1960 by Francis L. VerSnyder and Ray W. Guard, who were then both at the General Electric Company. They showed that the resistance to creep of certain nickel-based alloys could be increased dramatically if samples of those alloys were made in such a way that all the grain boundaries were parallel to an applied uniaxial stress, such as the centrifugal stress caused in turbine blades by high rates of rotation. When there are no grain boundaries perpendicular to the principal stresses, the samples are not as likely to creep or crack. In 1967 Barry J. Piearcey and I (then both at Pratt & Whitney Aircraft) showed that nickel-based superalloys could be even stronger if there were no grain boundaries at all—that is, if the entire sample were made from a single crystal—and if the samples were aligned in a specific orientation with respect to the applied force. These findings provided the inspiration for a major initiative by Pratt & Whitney to develop techniques for producing turbine blades with such properties.

To make a conventional turbine blade, molten metal is poured into a ceramic mold (which is preheated to about half the temperature of the melt) and allowed to solidify. The melt begins to solidify wherever it comes in contact with the mold, and the final result is a fine-grained polycrystalline structure in which the individual grains are oriented randomly.

In directional solidification, on the other hand, most of the mold is preheated to a temperature roughly equal to that of the molten metal; the bottom section of the mold is attached to a water-cooled copper "chill plate." The mold is held in a "hot zone" surrounded by a system of insulated heat baffles. The melt is poured into the mold and begins to crystallize in the region of the chill plate. Typically, many individual crystals form and grow at the chill plate. The entire mold is then slowly lowered and withdrawn, bottom first, from the hot zone. The crystals that formed at the chill plate then grow as long columns. The final result is a turbine blade made up of several long, columnar crystals with roughly the same orientation that are joined together along vertical planes. All the grain boundaries are roughly parallel to the direction in which the blade will be pulled by centrifugal forces.

A similar procedure can produce a blade with no grain boundaries at all. To make a single-crystal blade, the melt is poured into a ceramic mold that has a corkscrew-shaped "bottleneck" between the chill plate and the upper part of the mold. As the mold is withdrawn from the heat baffles, columnar crystals begin to grow, but the bottleneck is so narrow that only one of the crystals will grow through it. That crystal alone grows through the bottleneck. Even as the mold widens above the bottleneck, that crystal, becoming larger in diameter, is the only one to grow into the mold, and so the final blade (which is formed in the upper part of the mold) will be made of a single crystal.

Directional solidification is most useful for casting nickel-based superalloy turbine blades, but it can be adapted to other alloy systems as well. In particular it can be used to manufacture a new kind of material known as a eutectic superalloy. When a melt of nickel and aluminum is alloyed with a quantity of molybdenum and then directionally solidified, it can happen that all the molybdenum forms long filaments, which are embedded in a matrix of gamma and gamma-prime nickel-aluminum superalloy and are aligned parallel to the direction of solidification. The filaments of molybdenum act to reinforce the material in much the same way that graphite fibers reinforce the epoxy matrix in certain standard composite materials [see "Composites," by Tsu-Wei Chou, Roy L. McCullough and R. Byron Pipes, page 192]. The major difference between eutectics and conventional composites is that the fibers in a eutectic are less than one micrometer (a millionth of a meter) in diameter and are spaced only a few micrometers apart. It would be impossible to make such a composite by conventional techniques—say by assembling the fibers first and then pouring the matrix material over them.

Another advanced processing technique, superplastic forming, also dates to the early 1960's. When certain metals are processed in such a way that their grain sizes are less than about five micrometers, it is possible to stretch them by about 1,000 percent of their original length without breaking them. The reason is that the very fine grains deform slowly and slip past one another without breaking apart. Because of their remarkable capacity for being deformed, such superplastic materials can be forged into intricate shapes, eliminating many stages of machining and finishing.

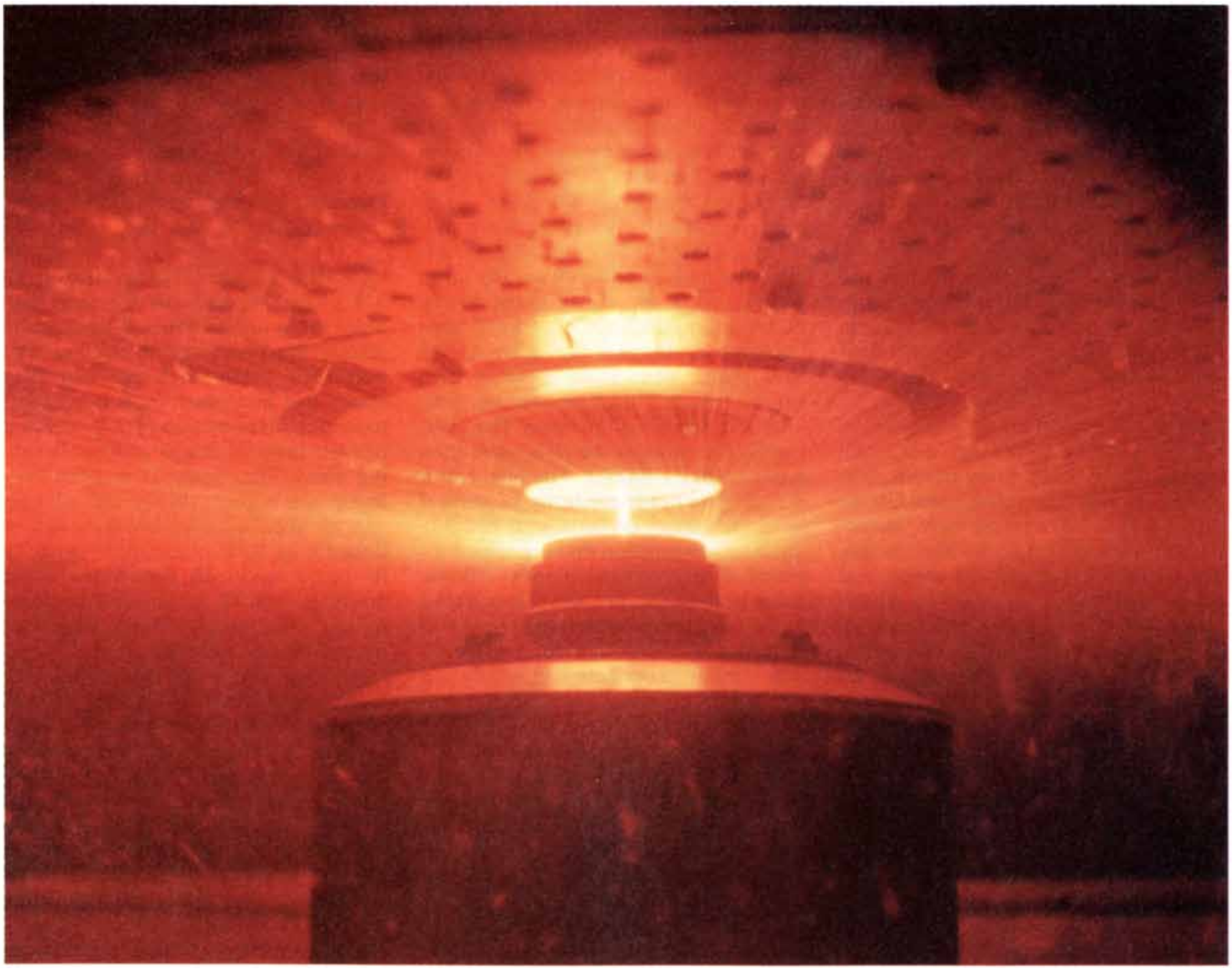
In 1963 Joseph B. Moore and Roy L. Athey of Pratt & Whitney discovered that certain fine-grained nickel-based superalloys can be made to flow superplastically. The necessary fine grain size is produced by working the material vigorously at a temperature just under the temperature at which gamma-prime crystals begin to form. It is critical that some gamma-prime particles be present because they prevent the matrix of gamma-phase material from recrystallizing to form larger grains. After the material has been made superplastic it is possible to work it, like a putty, into the desired shape. Then the shaped billet can be heat-treated, cooled rapidly and aged in order to produce a grain structure that is stronger and stabler at high temperatures than the fine-grained superplastic structure.

Superplastically formed materials are less expensive to machine and, when they are made from prealloyed fine powders, they exhibit remarkable chemical and microstructural uniformity. This feature has resulted in major improvements in the properties of the forged alloys, particularly in their resistance to low-cycle fatigue. Another benefit of such a homogeneous microstructure is that it can be transformed into a directionally aligned, columnar structure by gradient annealing, in which a heating element is passed slowly along the sample in a single direction. The resulting microstructure bears a superficial resemblance to the microstructure produced by directional solidification, but it has finer grains, is more homogeneous and can be crystallized to have a variety of textures.

Prealloyed powders can also be molded by a procedure known as hot isostatic pressing. The prealloyed powders are first packed into a thin-walled collapsible container that is a geometrically expanded version of the final shape to be molded. The container is put in a high-temperature vacuum in order to remove adsorbed gas molecules, and then it is sealed and placed in a specialized press. The entire assembly is exposed to very high pressures and temperatures, collapsing the mold and welding the powder together. Finally the container is stripped off and the formed metal is machined.

Hot isostatic pressing is not merely a way to form powders into predetermined shapes; it can also be used to heal defects in precast parts and to rejuvenate blades, vanes and other components that have weakened because of heavy use. Blades and vanes that have crept enough to have formed microscopic pores at grain boundaries can be restored to their original condition in the hot press, where the metal is pressed and welded together to fill the micropores. Hot isostatic pressing might also make it possible to build single components in which different sections are made of different alloys. For example, a turbine disk might be pressed isostatically from two alloy powders; the powder for making the rim might be of an alloy that is more creep-resistant, and the powder to make up the bore might be of an alloy that has a higher overall load-bearing capacity.

Often it is important to distribute very small amounts of one material evenly within a much larger



CENTRIFUGAL ATOMIZATION is one of several techniques for creating samples of rapidly solidified metal. In this method, developed by Pratt & Whitney, a stream of molten metal is poured onto a spinning plate, where it is broken into droplets and thrown outward by centrifugal force. Jets of very cold inert gas are blown through holes in the top of the apparatus. The gas jets cool the droplets, which solidify rapidly, forming a fine powder. Rapidly solidified metals have many potentially useful properties.

amount of another. One processing technique that is particularly effective for this kind of homogenization is mechanical alloying, which was introduced by John S. Benjamin of the International Nickel Company in 1970. Small particles of the various materials to be alloyed are placed in a high-speed ball mill, which consists essentially of an assembly of agitators and a large number of small stainless-steel balls. The agitators spin rapidly, causing the balls to collide with one another and with the small particles. The particles are repeatedly cold-welded to one another to form larger particles, which are themselves broken apart and welded to one another repeatedly. The final result is a powder made of very fine, homogeneous particles. This powder is subsequently consolidated and bonded by hot extrusion, and then it is hot-worked and directionally recrystallized.

Mechanical alloying is typically employed to disperse a fine powder of oxide particles within a metallic matrix usually made of a nickel- or cobalt-based alloy. The oxide particles "pin down" dislocations, much as gamma-prime crystals do in nickel-based superalloys, making the resulting alloy harder but not more brittle. Unlike the gamma-prime crystals in superalloys, the fine oxide particles do not coarsen, or grow, when they are heated, and therefore these so-called oxide-dispersion-strengthened alloys are stronger at high temperatures than alloys that are hardened by small crystals within a matrix.

Such alloys of the oxide-dispersion-strengthened variety have a particularly bright future. Improvements in techniques for processing them continue to reduce production costs while making possible the creation of materials with better and more reliable mechanical properties. In gas-turbine engines oxide-dispersion-strengthened alloys have found applications in the combustion chamber and stationary turbine vanes.

The processing technique that has caused perhaps the most interest in recent years is rapid solidification, in which molten metals are cooled at rates as high as a million degrees per second. Rapidly cooled alloys tend to be relatively homogeneous because there is not enough time for large grains to nucleate and form. Materials that have homogeneous structures are often strong, and they usually have high incipient melting points. The second-phase crystals (such as those of gamma-prime) that do form are small and uniformly distributed, and they strengthen the alloy by pinning dislocations. They also pin the alloy's own grain boundaries in place, helping to keep the grain structure from coarsening in high-temperature applications. Moreover, rapid solidification can give rise to metastable phases: crystalline or near-crystalline phases that are somewhat stable but not as stable as the phases the alloys form when they are cooled slowly. Metastable phases have a number of interesting properties that are only now beginning to be explored in detail.

Several industrial research groups have been making systematic investigations of the applications of rapidly solidified alloys. For example, the Allied Corporation has developed a new class of strong, rapidly cooled aluminum alloys, which have a strength-to-weight ratio equal to or higher than that of titanium alloys at moderate-to-high temperatures. They have also turned out to be unusually resistant to corrosion, although it is not yet at all clear why. These rapidly cooled aluminum alloys could replace titanium in parts of the compressors of gas-turbine engines.

There are several ways to produce rapidly cooled alloys. The simplest way is splat cooling, in which droplets of molten metal are projected onto a cold surface. Another method is atomization, in which a fine spray of droplets is cooled by an atmosphere of extremely cold inert gas. Pratt & Whitney has developed a system in which a thin stream of melt falls onto a rapidly spinning wheel, which breaks the stream into droplets and throws them out into a cold atmosphere; this method produces fine powders of rapidly cooled alloy, which can then be consolidated by hot extrusion to form a completely homogeneous product. General Electric has combined melting, consolidation and shaping into a single process in which, with the aid of a plasma flame, rapidly cooled alloy is applied as a thin coating on a preexisting component. The deposited alloy is highly resistant to thermal fatigue, making it an ideal coating for parts in the combustion chamber of a gas-turbine engine.

One of the most versatile rapid-cooling techniques employs lasers with high power densities. The laser beam is passed rapidly over a material's surface, forming thin layers of molten material. The thin layers are cooled by the bulk of the solid, which is not affected by the laser beam. It is possible by this technique to achieve cooling rates as high as 10 million degrees per second. The advantage of this so-called laser-glazing process is that the surface microstructure of a material can be modified without affecting the underlying substrate. It is also possible to build up thicker layers of rapidly cooled material incrementally, by continuously delivering prealloyed powder to the surface and passing the laser back and forth rapidly. Quite complex shapes can be produced if the laser is under sufficiently versatile control. The potential applications for laser glazing include hardening the tips of turbine blades and building up knife-edge seals on rotating parts.

Advances have also been made in techniques for coating and bonding metals. Coatings are particularly important, because they make it possible to choose a bulk metal that has desirable mechanical properties even if it is not well suited to corrosive environments. New bonding techniques make it possible to produce a part in many thin layers, eventually brazing them to form a single finished component. One application for these techniques is in the manufacturing of air-cooled turbine blades, in which there are small channels, or air passages. The blades are fabricated as a series of many thin segments, each of which is photo-etched to cut out sections of the channels. The thin segments are joined by diffusion bonding or diffusion brazing, in which a thin film with roughly the same composition as the segments but a slightly lower melting point is sandwiched between etched segments. The segments are pressed together at a high temperature and in a vacuum, and the bonding material diffuses into the two mating surfaces.

The benefits derived from advanced metals and processing techniques are not limited to the gas-turbine engine. They have had considerable impact on many other evolving systems. For example, superalloys have proved to be valuable in systems for converting and generating energy, where they provide great strength at high temperatures and in aggressive environments. Advanced processes such as superplastic forming have been adapted for many purposes, including the fabrication of light, intricate honeycomb structures of high strength and rigidity for airframes. Hot isostatic pressing makes possible the production of specialty alloys for surgical implants. As processing costs continue to decline, other areas of application will emerge. Eventually even the more general industrial sectors of the economy, such as the transportation industry, will benefit from research on advanced metal alloys and processes.

Advanced Ceramics

These nonmetallic, nonpolymeric materials are hard, resist heat and chemicals and can be designed to have special electrical properties. Research Focuses on a major shortcoming: a tendency to crack easily

by H. Kent Bowen

For thousands of years clay, the first processed ceramic, has been the primary raw material for pottery, bricks and tiles. It is therefore understandable that such unsophisticated products first come to mind when most people think of ceramics.

Materials scientists, on the other hand, generally define ceramics as including all solid materials that are neither metals nor polymers (although they may contain metallic and polymeric elements as constituents or additives). Ceramics can be fabricated from a wide variety of raw materials other than clay (some of which are not found in nature), and they come in a wide variety of forms: glasses, crystallized glasses, monolithic crystals, conglomerations of small crystals and combinations of these. They serve as abrasives and cutting tools, as heat shields and electrical insulators, and as lasing crystals, nuclear fuels and artificial bone implants. The diverse applications of ceramics make them not only common materials but also indispensable ones in modern society.

In all their applications ceramics are valuable primarily for their ability to withstand heat and chemical attack. These virtues stem from the strong bonds that hold their constituent atoms in place. The nature of those bonds also imposes on ceramics a critical drawback, however: brittleness. A brittle material does not deform under load and so, as anyone who has ever dropped a piece of chinaware will attest, it has a propensity to crack and break all too easily. This unfortunate property makes a ceramic particularly sensitive to minute imperfections in its microstructure that serve as starting points for cracks. Hence much effort in ceramic research has been devoted to developing new processing techniques that minimize these microscopic flaws as well as to designing new compositions and microstructures that suppress the growth of cracks.

Recent advances in ceramics not only have succeeded in alleviating the problem of brittleness but also have provided greater control over aspects of composition and microstructure that govern other physical properties. Such control makes it possible to tailor ceramics to fulfill special chemical, thermal, mechanical and electrical requirements no other material can satisfy. Indeed, advanced ceramics have played critical roles in the development of new technologies such as computers and telecommunications, and they will continue to play a leading role in the technologies of the future.

A ceramic's characteristic properties derive from its structure, both at an atomic level and at scales ranging from micrometers (millionths of a meter) to millimeters. At the atomic level two types of bonding are encountered in ceramics: ionic and covalent. In ionic bonding electrons are transferred from one atom to a neighboring atom. The atom giving up the electrons thereby becomes positively charged and the atom accepting the electrons becomes negatively charged. The opposite ionic charges thus created bind the atoms of the material together.

In covalent bonding electrons are shared more or less equally between neighboring atoms. Although the electrostatic force of attraction between adjacent atoms is less than it is in ionic bonding, covalent bonds tend to be highly directional, meaning that they resist the motion of atoms past one another. The hardest material known, diamond, is composed of covalently bonded carbon atoms.

Whether the bonds are mostly ionic or mostly covalent, they can arrange atoms into groups, called unit cells, that may be repeated periodically throughout the material. Such an ordered array of unit cells constitutes a crystal. If no periodicity beyond the local unit cell is evident, the material is noncrystalline. In many cases the same combinations of atoms can produce a crystalline or a noncrystalline structure depending on whether the atoms have enough time during the forming process to arrange themselves in a periodic manner. For instance, if silica, or silicon dioxide (SiO_2), is melted and allowed to cool slowly and in a controlled way, the silica molecules arrange themselves into a lattice that has long-range order to produce cristobalite crystals (a type of quartz). On the other hand, if a silica melt is cooled rapidly, the molecules do not have enough time to construct a crystal lattice and are "frozen"in an irregular arrangement to produce a noncrystalline substance: silica glass.

It is at this fundamental, atomic level that ceramics can be distinguished

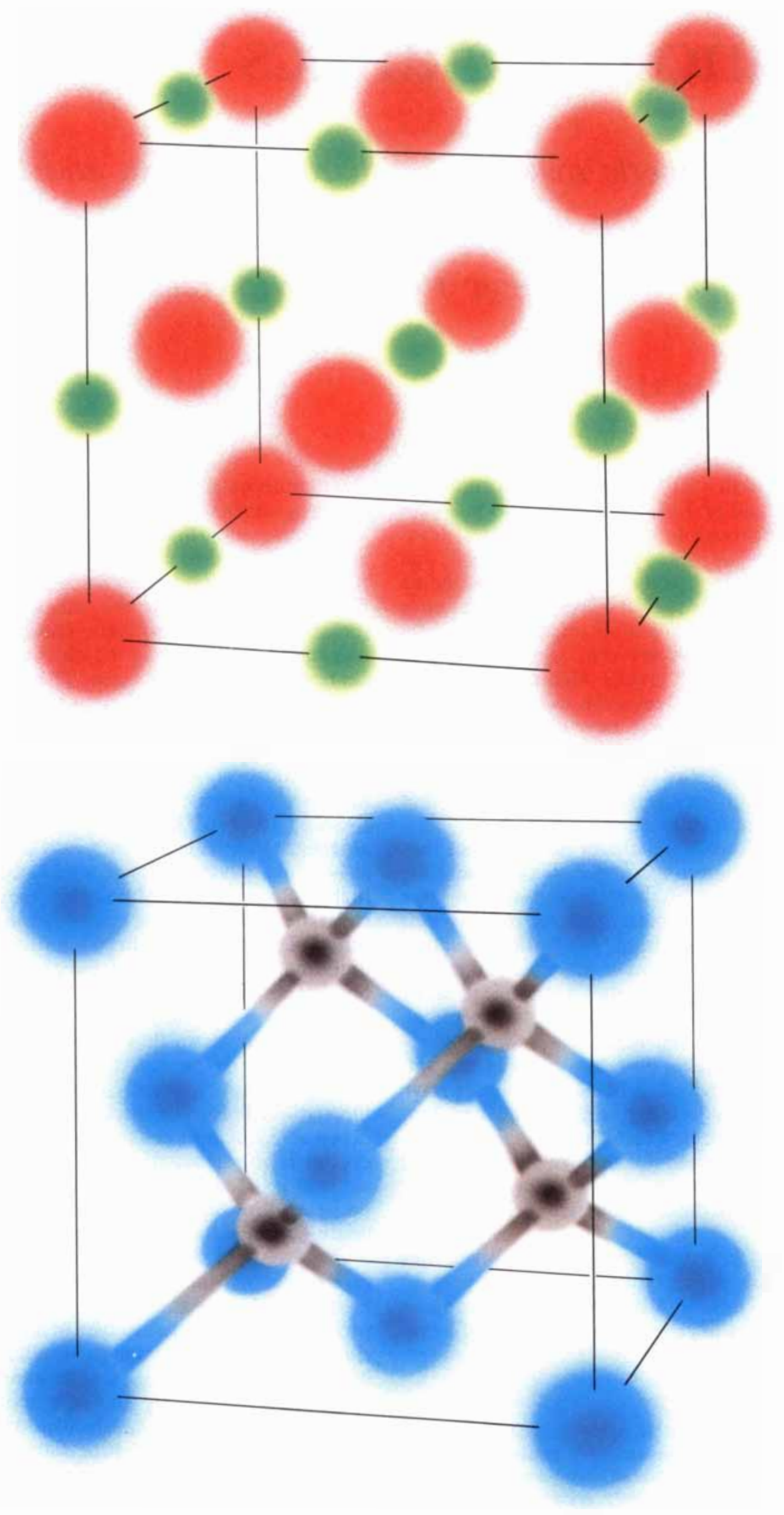
TWO KINDS OF GRAINS, or tiny crystals, are made visible in a polarized-light micrograph of a sample (enlarged about 400 diameters) of a glass-ceramic material produced from slag, the waste product of metal smelting. Columnar grains have formed at the surface of the material and grown inward, where they meet feathery grains. Glass-ceramics constitute a new type of ceramic material that combines the inherent ease of processing noncrystalline ceramics, or glasses, with the durability and heat resistance of crystalline ceramics. Glass-ceramic objects are made by melting raw materials into a viscous glass, shaping the object from the pliable material and then causing grains to form in the shaped material. Crystallization in the glass-ceramic object is promoted by the inclusion of nucleating agents in the melt and by heat treatment. This glass-ceramic, composed of silica, or silicon dioxide (SiO_2), calcium oxide (CaO) and several other metal oxides, may have a practical application as wear-resistant tiles. The micrograph was made by Rosalia N. Andrews and Martha R. Fletcher of the University of Alabama at Birmingham.

from other materials. Whereas ceramics typically have strong hybrid ionic-covalent bonds that limit electron motion, atoms in metals form lattice structures, through which the outermost electrons of the atoms can move freely. Organic substances are composed of molecules based on carbon and hydrogen atoms, and the molecules tend to occur in polymers, or long chains, rather than in three-dimensional crystalline structures.

The diversity of atomic structures (there are 14 classes of unit cells) and the possibility of extensive substitution of one element for another in the structure allow for a seemingly infinite variety of ceramics that have a wide range of properties. One exemplary case is that of aluminum oxide. If chromium atoms are interspersed in monolithic crystals of aluminum oxide, ruby crystals are created that serve as the lasing medium in lasers. The interspersion of titanium atoms in similar aluminum oxide crystals yields sapphires. Polycrystalline forms (consisting of numerous small crystals, called grains) of aluminum oxide can be transparent enough to make windows that withstand high pressures and temperatures. In the form of loose grains the same ceramic is corundum, a hard abrasive; in the form of fine particles in a silica-glass matrix it is the basis of electrical insulators and refractory (heat-resistant) bricks.

The atomic structure of ceramics gives them a chemical stability that is manifested as imperviousness to environmental degradation, such as dissolution in solvents. Also, because many ceramics are composed of metal oxides, further oxidation (whether by combustion or by other chemical reaction) is often impossible. (In essence, a metal-oxide ceramic has already been "burned" or "corroded," so that the final ceramic object cannot be further subjected to either of these degradations.) The strength of the bonds in ceramics also endows them with a high melting point, hardness and stiffness.

Unfortunately the strength of the bonds in ceramics also prevents planes of atoms from sliding easily over one another; the material cannot deform (as ductile metals such as copper do) to relieve the stresses imposed by a load. As a result ceramics maintain their shape admirably under stress until a certain threshold (the fracture threshold) is exceeded; then the bonds suddenly give way and the material fails catastrophically. A further consequence of brittleness is that ceramics can withstand compressive loads (forces that squeeze the material together) far better than they can withstand ten-

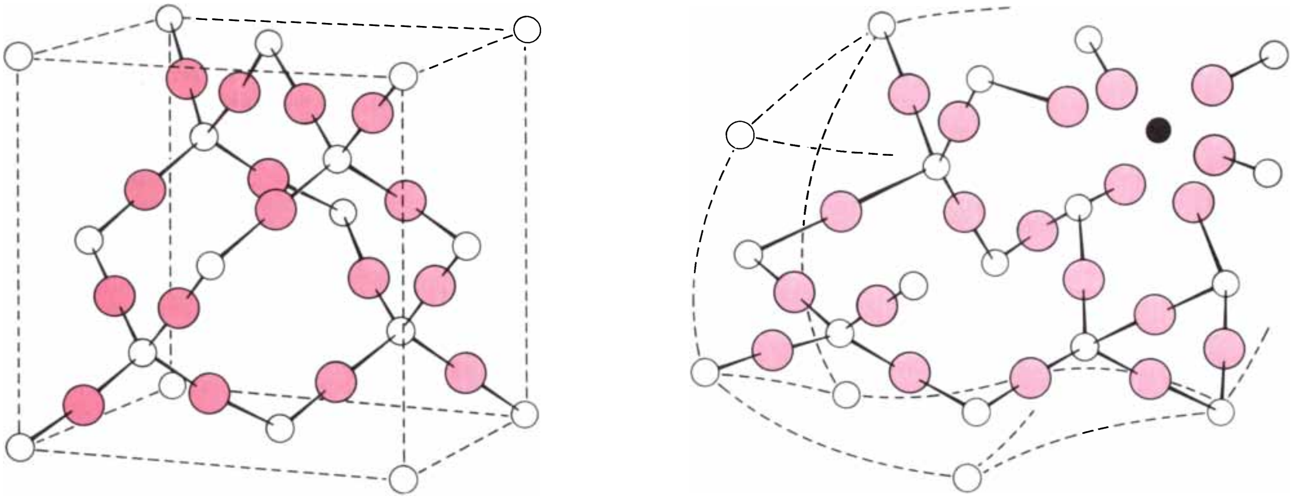


BONDING IN CERAMICS is both ionic (*top*) and covalent (*bottom*). In ionic bonding electrons are transferred from an atom to a neighboring one. The donor atom thereby becomes positively charged and the acceptor atom becomes negatively charged. The electrostatic force between the atoms keeps the atoms in place. In covalent bonding electrons are shared more or less equally between neighboring atoms. Unlike ionic bonds, covalent bonds (represented here by visible connections between atoms) tend to be highly directional and resist the sliding of planes of atoms past one another. The diagrams are idealized cases. An actual ceramic has a hybrid of the two bonds among its constituent atoms.

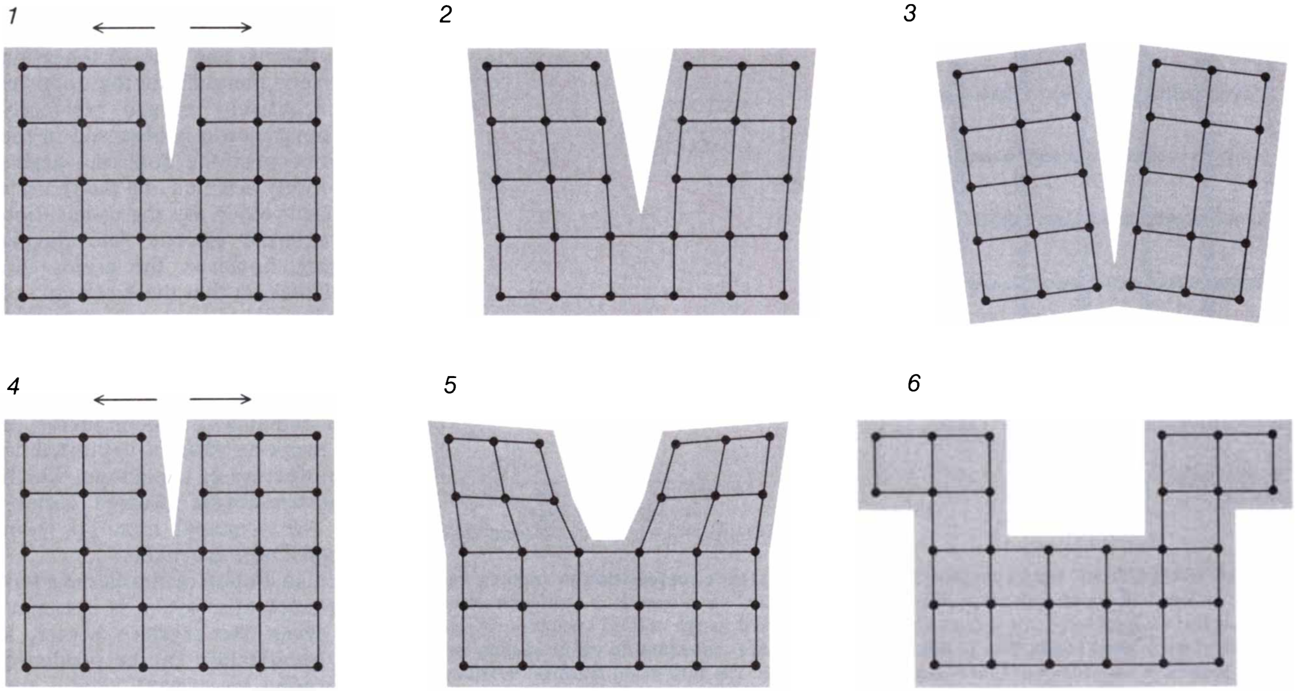
sile loads (forces that pull the material apart) or shear loads (forces that cause planes of material to slide in opposite directions). The reason is that whereas under compressive loads incipient cracks tend to be squeezed shut, under tensile or shear loads the crack surfaces tend to be pulled apart, further widening the cracks.

Ceramic materials could be made much more crack resistant if minuscule defects such as voids or chemical impurities between the material's grains could be eliminated. Any applied stress tends to be concentrated at the sites of these flaws. Because the ceramic material cannot deform to relieve the concentrated stress, the fracture threshold can easily be exceeded at the sites of flaws even though the bulk of the material remains below the threshold. When the threshold is exceeded at a defect site, a crack develops. Because the crack also concentrates stress, it propagates quickly through a ceramic, ultimately causing the material to fail.

Resistance to brittle failure (the degree of difficulty with which cracks propagate through a stressed materi-



CRYSTALLINE AND GLASSY CERAMICS can be made from the same combinations of elements. The difference in form between the materials lies in the three-dimensional arrangement of their atoms. A silica crystal (*left*) is made up of a fundamental pattern of silicon (*white*) and oxygen (*color*) atoms that is repeated regularly throughout the material. Silica glass (*right*), on the other hand, shows no long-range periodicity in its atomic structure. Impurities (*black*) in the glass further distort the structure by severing bonds between oxygen and silicon atoms. A crystal is formed from a silica melt if the liquid is cooled gradually, allowing the atoms enough time to arrange themselves in the periodic structure. If the melt is cooled rapidly, silica glass is formed.



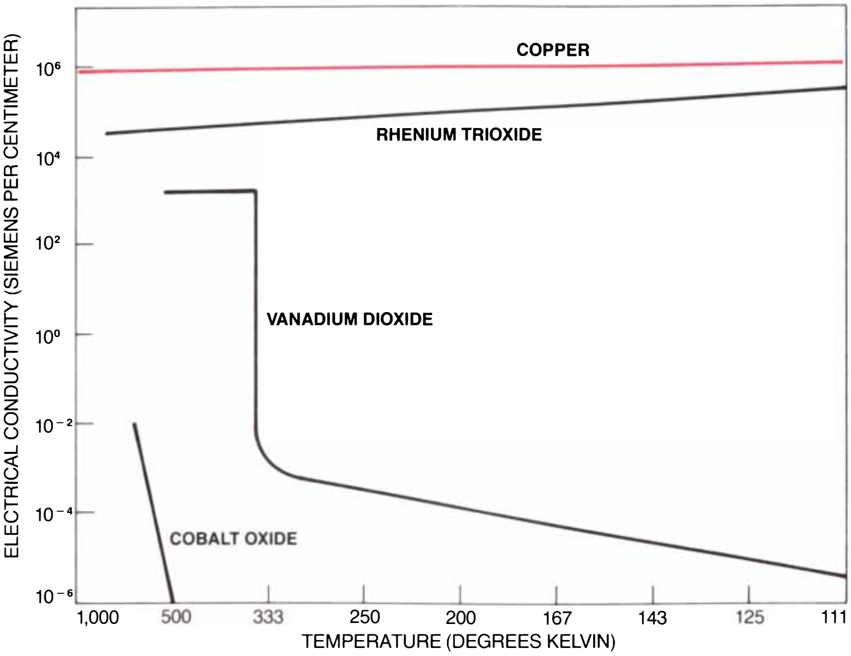
BRITTLE MATERIALS such as ceramics have a crystal structure that does not readily deform. As a consequence a narrow crack, which concentrates tensile stresses (*arrows*) at its tip to exceed the threshold at which the material's bonds are broken, can quickly work its way through a ceramic (*1–3*), causing the material to fail catastrophically. A similar crack in a ductile material (*4*) would be widened and blunted as bonds deform, break and rejoin, allowing planes of atoms to slide past one another (*5, 6*).

al) is measured quantitatively as fracture toughness. Most metals have fracture-toughness values greater than 40 megapascals (MPa) per square-root meter; relatively brittle metals such as cast iron can have a fracture toughness as low as 20 MPa per square-root meter. Conventional ceramics and glass materials, in contrast, have fracture-toughness values of only about 1 MPa per square-root meter.

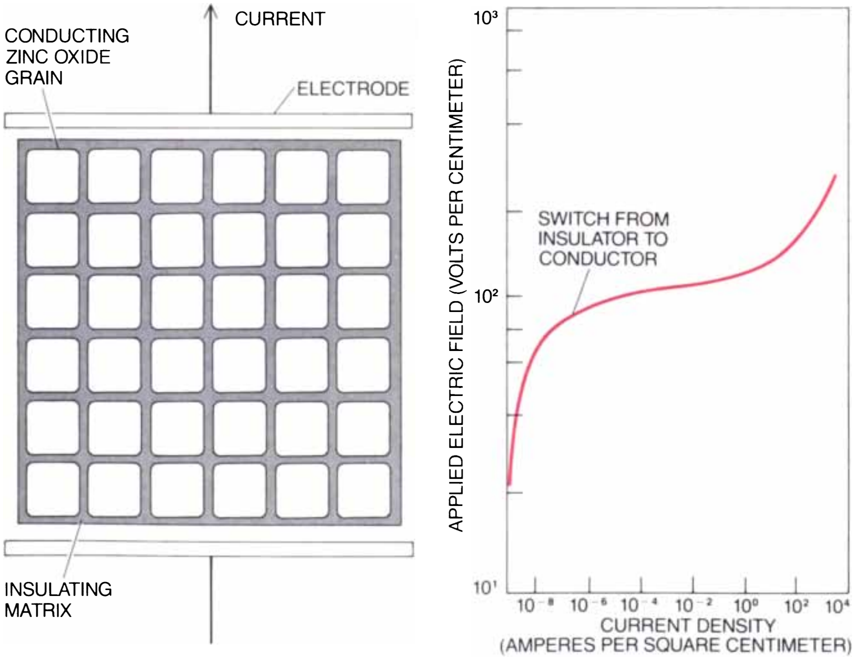
Still other macroscopic properties of ceramics arise from peculiarities in the way atoms are arranged into crystals. For example, the crystal structure of cobalt oxide allows electrons, if they are properly excited, to travel through the crystal lattice much as they would in a semiconductor such as silicon. Vanadium dioxide also acts as a semiconductor at low temperatures for the same reason. Unlike cobalt oxide, however, vanadium dioxide undergoes a slight modification in its crystal structure at about 330 degrees Kelvin (60 degrees Celsius), and electrons in the material then behave as they would in a metal conductor. The crystal structure of rhenium trioxide, in contrast to that of the other two metal oxides, allows it to conduct electricity like a metal regardless of its temperature.

The so-called ferroelectric ceramics provide an even better example of the properties that result from a material's atomic architecture. Because the crystal grains found in ferroelectric ceramics have an uneven distribution of charge in their unit cells, they are polarized, that is, one side of the grain is positively charged and the opposite side is negatively charged. Normally no net polarization is observed in the ceramic because the polarized grains are randomly oriented and the charges cancel each other. By the application of an external electric field during processing, however, the grains can be reoriented so that the directions of their polarization line up and impart a macroscopically detectable charge distribution on the material. Even when thus polarized, however, the ceramic remains a nonconductor. It is this property that is exploited in the manufacture of capacitors, which store electric charge. (Indeed, ceramics are the principal material from which capacitors are made.)

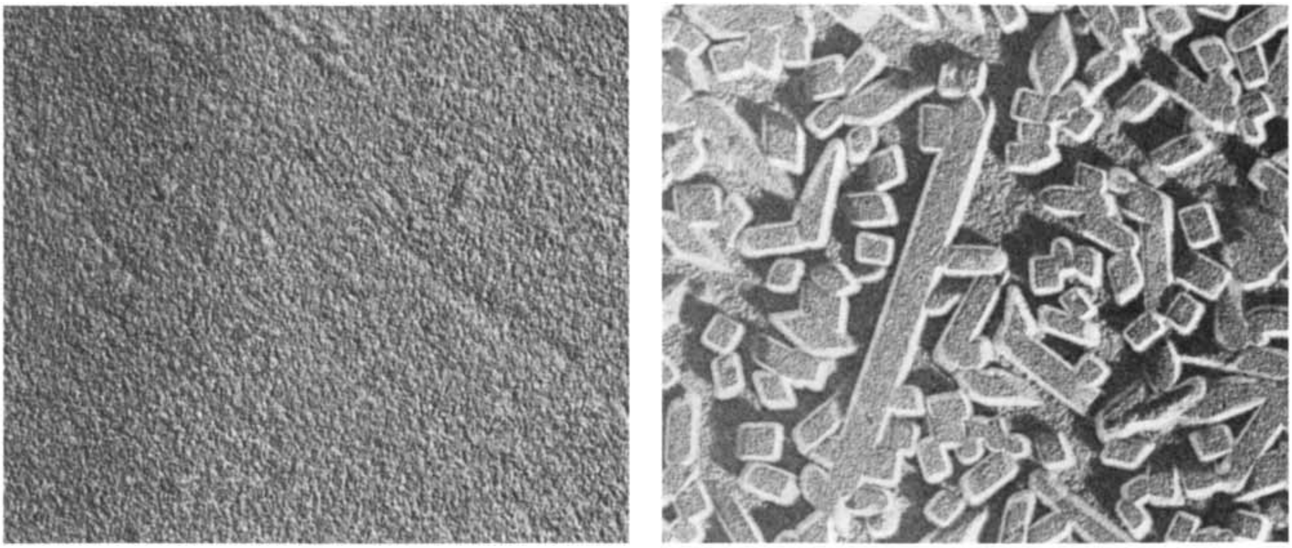
If the distribution of charges in a ferroelectric-ceramic crystal is not symmetric about the crystal's center, a shift in polarization can be produced by deforming the crystal. This is the basis of piezoelectric ceramics. When such ceramics are mechanically deformed, they develop a considerable electric charge; conversely, when they



ELECTRICAL PROPERTIES of ceramics are a function of their crystal structure and the allowable energy states of the electrons that form bonds, both of which are determined by atomic composition. Cobalt oxide (CoO) has a structure that enables properly excited electrons to travel through the crystal lattice, much as they would in a semiconductor such as silicon. Vanadium dioxide (VO_2) also behaves the way a semiconductor would, but at 330 degrees Kelvin (about 60 degrees Celsius) it undergoes a slight change in crystal structure and electrons can then travel through it as they would travel through a metal conductor. Rhenium trioxide (ReO_3), unlike the other two metal oxides, is a conductor regardless of temperature. The conductivity of copper is shown for comparison.



MICROSTRUCTURE can be manipulated along with atomic composition to endow a ceramic with unique electrical properties. Zinc oxide (ZnO) is normally a semiconductor, but if certain impurities (called dopants) are interspersed in the crystal structure, it can be made into a good conductor. If doped ZnO grains are embedded in an insulating ceramic matrix, a varistor (variable resistor) can be made. The insulating material between the ZnO grains prevents current from flowing through the varistor at low voltages. At high voltages, however, electrons have enough energy to surmount the conduction barrier between the grains, and they travel readily through the varistor. The voltage at which a varistor switches from poor to good conductance is controlled by varying the size and doping of the ZnO grains and the thickness of the insulating layers between the grains.



EXTREMELY SMALL GRAINS can be crystallized in glass-ceramics. The electron micrographs, made at the Corning Glass Works, show a noncrystalline aluminosilicate glass (*left*) and the same material after it has been heat-treated to produce crystalline grains (*right*). The sample has been enlarged about 70,000 diameters. Because smaller, more uniform grains improve a ceramic's performance, materials scientists are turning to glass-ceramic processing methods as one way of producing advanced ceramics.

are subjected to an electric field, they deform. Because piezoelectric ceramics efficiently convert mechanical energy into electrical energy or vice versa, they are at the heart of transducers found in sonar systems and medical ultrasonic instruments. The charges generated by mechanical deformation in some piezoelectric ceramics can amount to several tens of thousands of volts. The sparks that can be drawn from the voltage thus produced are used for ignition in gas heaters, cooking stoves and cigarette lighters.

The properties implicit in a ceramic's atomic structure can sometimes be fruitfully combined with a particular microstructure to give the material special desired properties. One such case is the manufacture of zinc oxide varistors, or variable resistors. Zinc oxide (ZnO) crystals are normally semiconducting, but they can be made into good electrical conductors by including certain impurities in the crystalline structure (a process called doping). If an array of doped ZnO grains is embedded in an insulating ceramic matrix, the electrical properties of the resulting material can be made highly nonlinear. At low voltages the material exhibits low electrical conductance because the insulating matrix prevents the passage of an electric current between ZnO grains. At high voltages, however, the electrons that carry the current have enough energy to surmount the insulating barriers between the conducting ZnO grains, and the result is a highly conductive material. The voltage at which the switch from poor conductor to good conductor takes place can be set by varying the microstructure: the ZnO-grain size and the thickness of the insulating layers between the grains. Hence such ZnO varistors have found application as automatically resetting circuit breakers in electrical devices of virtually any voltage.

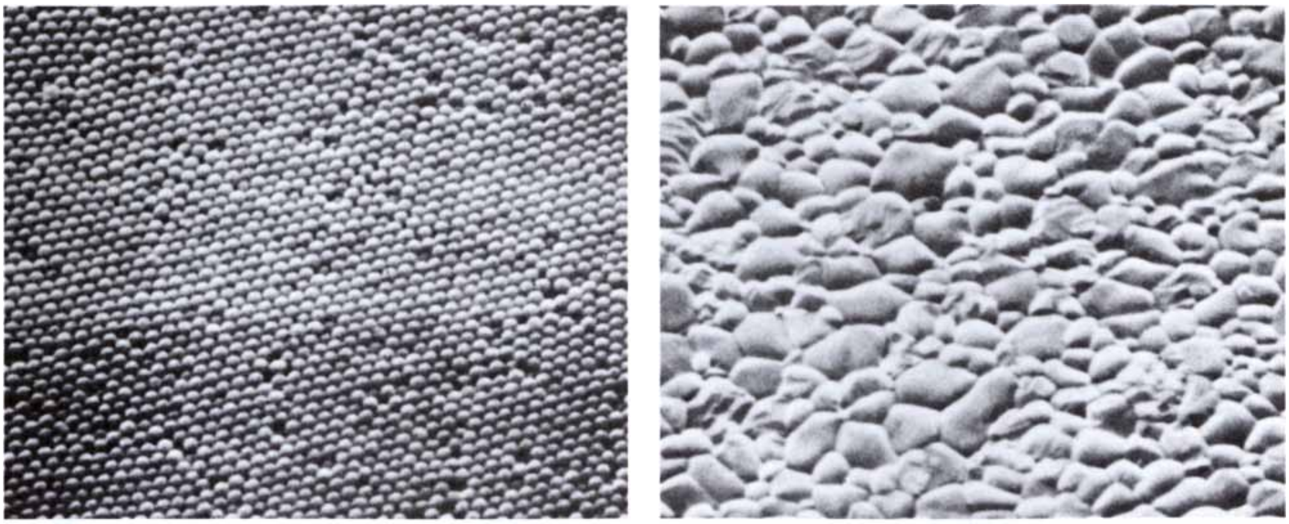
A ceramic's chemical composition and microstructure ultimately determine all its macroscopic properties. These in turn are determined by processing methods. Because it is easier in many respects to process ceramics (like metals and plastics) from a molten state, glasses and monolithic crystals are processed in this way. One type of modern ceramic, the so-called glass-ceramic, combines the ease of processing glass with the durability of polycrystalline ceramics.

In the processing of glass-ceramics, which was pioneered at the Corning Glass Works about 30 years ago, the raw materials are melted and the object is shaped while the material is in a glassy state. Special nucleating agents included in the melt and subsequent heat treatment promote the growth of tiny crystals within the glass. Because of the crystalline grains in them, glass-ceramics display greater strength and high-temperature resistance than conventional, noncrystalline glasses.

Although the soft, viscous glass that can be got from a ceramic melt is amenable to quick bulk processing, the full range of properties of advanced ceramics often cannot be reached if the material is in a glassy state. That is why most advanced ceramics are ordinarily fabricated by a multistage process that complicates considerably the task of manipulating composition and microstructure.

The process for making advanced ceramics is remarkably similar in principle to the one by which traditional clay artifacts are made today. To mass-produce fired pottery, natural minerals are first milled and blended into a fine clay powder. Water is added to form a plastic mass. The mass is shaped by conventional techniques such as injection molding (in which the clay is forced into a closed mold), extrusion molding (in which the clay is forced through a die that has the desired cross section) or slip casting (in which a clay-water slurry is poured into a porous mold, which absorbs the excess water). The shaped object is dried in air before being placed in a kiln. There it is fired at a temperature well below that at which the ceramic would completely melt, a process called sintering. During sintering the clay particles are "welded" together so that most voids between particles are removed, and consequently the object shrinks.

Similar steps are followed in the manufacture of advanced ceramic products, except for the fact that organic-polymer binders are normally added, instead of water, to convert the fine starting powder into a malleable mass. The binders are then burned out in the sintering process. Other organic chemicals, called deflocculants, may also be added to prevent the agglomeration of the powder into lumps, which results in uneven sintering and the formation of voids. Sometimes the application of pressure before or during sin-

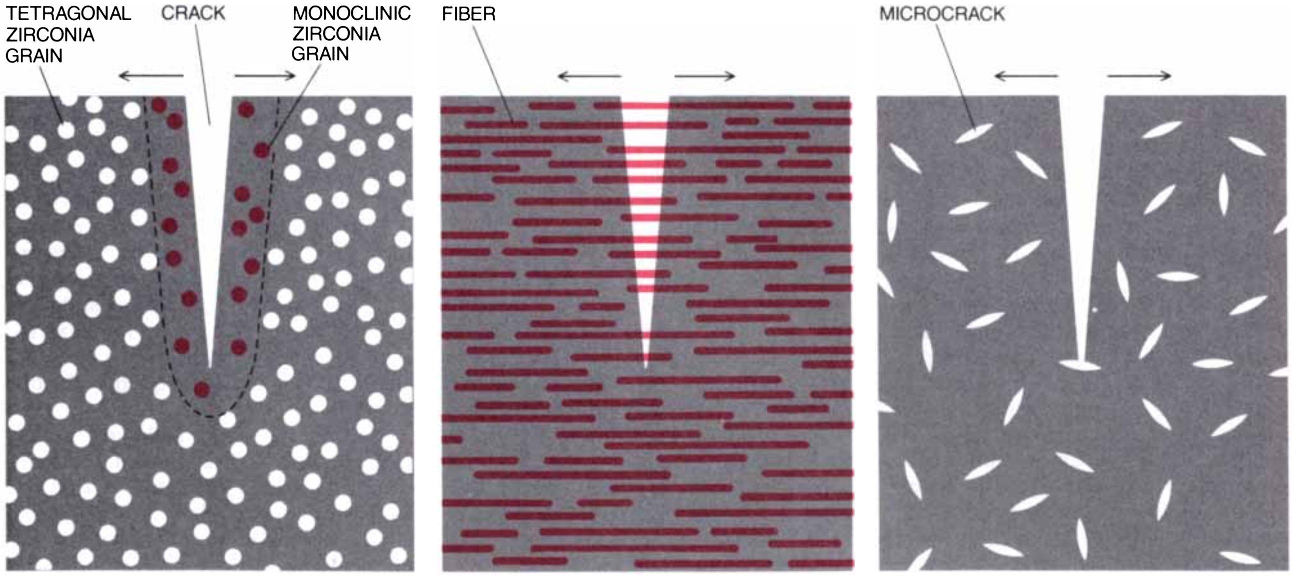


CHEMICAL SYNTHESIS of fine powders, from which ceramics are made, is another way to ensure extremely small grains in the ceramic material. At the Massachusetts Institute of Technology a technique has been developed for precipitating particles of titania, or titanium dioxide, from a solution. The chemically pure, uniform particles are less than a micrometer (a millionth of a meter) in diameter. As is shown in these electron micrographs, such particles can be packed so tightly (*left*) that there are virtually no voids between the grains in the ceramic (*right*) produced when the particles are sintered: "welded" together by heating to a temperature well below that at which the material would totally melt. Because of its void-free microstructure, such a ceramic is tough.

tering helps to make the material denser by "squeezing" out voids in the powder mass; it also helps to reduce uneven shrinkage and cracking.

Since the Achilles' heel of a ceramic material is its propensity for brittle failure, and since such microscopic defects as voids, agglomerations and chemical impurities are the sites where cracks originate, most of the current research in ceramics has been directed toward eliminating such defects. One way to do this is to start with an extremely fine powder of high chemical purity that can be tightly packed before sintering.

At the Massachusetts Institute of Technology we have developed a way to precipitate out of solution uniform titania, or titanium dioxide (TiO_2), particles that are less than a micrometer in diameter. The particles are then suspended in another solution to which organic polymers are added. The polymers are absorbed onto the surface of the particles, preventing



TOUGHENING MECHANISMS, by which a crack in a ceramic can be arrested, complement new processing techniques that seek to eliminate crack-initiating imperfections. Transformation toughening (*left*) relies on a change in crystal structure (from tetragonal to monoclinic) that zirconia, or zirconium dioxide (ZrO_2), grains undergo when they are subjected to stresses at a crack tip. Because the monoclinic grains have a slightly larger volume, they can "squeeze" a crack shut as they expand in the course of transformation. Ceramics can also be made crack-resistant by interlacing with fine ceramic fibers (*middle*), as is the case in composite materials. The fibers span a crack and keep it from becoming wider and growing. A third way to stop a crack is by spreading the stresses concentrated at its tip over a larger surface. This can be accomplished if minute cracks, called microcracks (*right*), are purposely created in the ceramic material during processing. When an approaching crack merges with a microcrack, its tip is blunted.

them from coming close enough to agglomerate. The polycrystalline ceramic that results after controlled packing and sintering of the particles is of virtually theoretical density, that is, there are no voids among its crystal grains. Because of its void-free microstructure, the material is very strong and tough.

Another method, also developed at M.I.T., can produce minute particles of high chemical purity. A gaseous compound of silicon and hydrogen is heated with a high-power carbon dioxide laser. The brief but intense application of heat decomposes the gas, releasing the silicon in the form of extremely fine particles. By suspending these particles in a solution that allows their electric charge to be controlled, they can be made to pack tightly together into a defect-free structure.

These new processing methods allow materials scientists to control a ceramic's structure over scales varying by eight orders of magnitude: at the atomic level (by controlling chemical purity and sintering temperature and pressure), at a scale up to 100 times the size of an atom (by controlling particle size and particle-surface phenomena), at a scale measured in thousandths of a millimeter (by controlling grain and pore size through proper packing of the powder) and finally at the macroscopic scale of the product being manufactured.

In conjunction with better processing methods, which are designed to lessen the number of crack-initiating flaws, new ways to toughen ceramics are being developed that arrest cracks once they spring from tensile or shear loads. One method of attaining crack resistance is transformation toughening. It exploits a transformation of the crystal structure of zirconia, or zirconium dioxide (ZrO_2), that is induced by stresses at a crack tip. This change increases the volume of the zirconia crystal by from 3 to 5 percent. Hence an advancing crack approaching zirconia grains embedded in a ceramic matrix causes the grains to expand. Because the expansion results in a local compression of the matrix, the crack is essentially pinched shut and thereby arrested. Such zirconia grains have already been incorporated into many ceramics, some of which exhibit a fracture toughness greater than 15 MPa per square-root meter.

Another promising way to achieve added toughness is to interlace fine ceramic fibers in a ceramic or glass matrix. As in a polymer-fiber composite, the ceramic fibers span cracks and thereby keep them from widening and growing. Silicon carbide fibers have already been incorporated into glass, glass-ceramic and ceramic materials, and the resulting composites have shown significant resistance to brittle failure uncharacteristic of monolithic ceramics.

The principle behind a third method of toughening is the same one that underlies a common procedure for arresting visible cracks in steel plates. The idea is that blunting the tip of the crack will dissipate the stresses at the tip onto a larger area and so reduce them below the fracture threshold. In the case of steel plates this is done by drilling a hole at the crack tip. In the case of ceramics minute cracks, called microcracks, are purposely dispersed throughout the material in the course of its processing. When a crack tip reaches one of the microcracks, the crack is similarly blunted.

These advances and others in processing and microstructural design have allowed ceramists to synthesize entire classes of new materials whose unique properties no metal or organic material can duplicate. By virtue of these properties ceramic components have played and will continue to play a major if not critical role in the development of products, manufacturing processes and indeed entire industries. Advanced ceramics act as technology "enablers," meeting the special demands that nascent technologies place on materials.

Two examples of the enabling role ceramics have played in the recent past are the development of ferrite magnets for magnetic core memory, without which modern high-speed computers could not have been created, and the development of silica-based optic fibers, without which telecommunication systems would not have been able to meet future requirements economically.

Other such examples from the past could be cited, but it is the potential new applications of advanced ceramics that have scientists and engineers in many fields eagerly looking toward the future. For example, ceramics are now being incorporated into internal-combustion engines. The main benefits that can accrue from their incorporation are higher operating temperatures and a lower overall engine weight, both of which translate into higher efficiency. Also, because of their excellent wear resistance, ceramic components do not require extensive lubrication. The Nissan Motors Company, the Japanese automobile manufacturer, has already introduced a vehicle with a silicon nitride turbocharger rotor in its engine. The Cummins Engine Company, Inc., has been testing a diesel truck engine with ceramic piston caps, bearings and cylinder liners that enable the engine to run without a cooling system. Various U.S. firms are developing ceramic gas-turbine engines for automobiles, and Rolls-Royce Limited is experimenting with similar engines for helicopters.

Ceramics that change their electrical properties when they are exposed to certain chemicals also have many potential applications. Liquid or gaseous molecules interacting with such a ceramic in the form of a porous pellet, for example, could change the ceramic's electrical resistance, which is easily measurable. A sensing device based on such a principle is simple in design, often requiring only a pair of electrical contacts. The nonreactivity and corrosion resistance of ceramics would allow sensors made from these materials to perform considerably better in harsh chemical environments than conventional sensors can.

One such device, which has thousands of potential applications in air-conditioning systems, dryers and respiratory equipment, is a humidity sensor. Other ceramic sensors have been developed to detect the presence of methane, the chief constituent of natural gas; they could improve safety in homes where the gas is used for heating or cooking. Ultimately a single ceramic device that could sense temperature, pressure, light and heat, in addition to certain chemicals, could be coupled with a microprocessor to control machines in the home, in transportation and in factories.

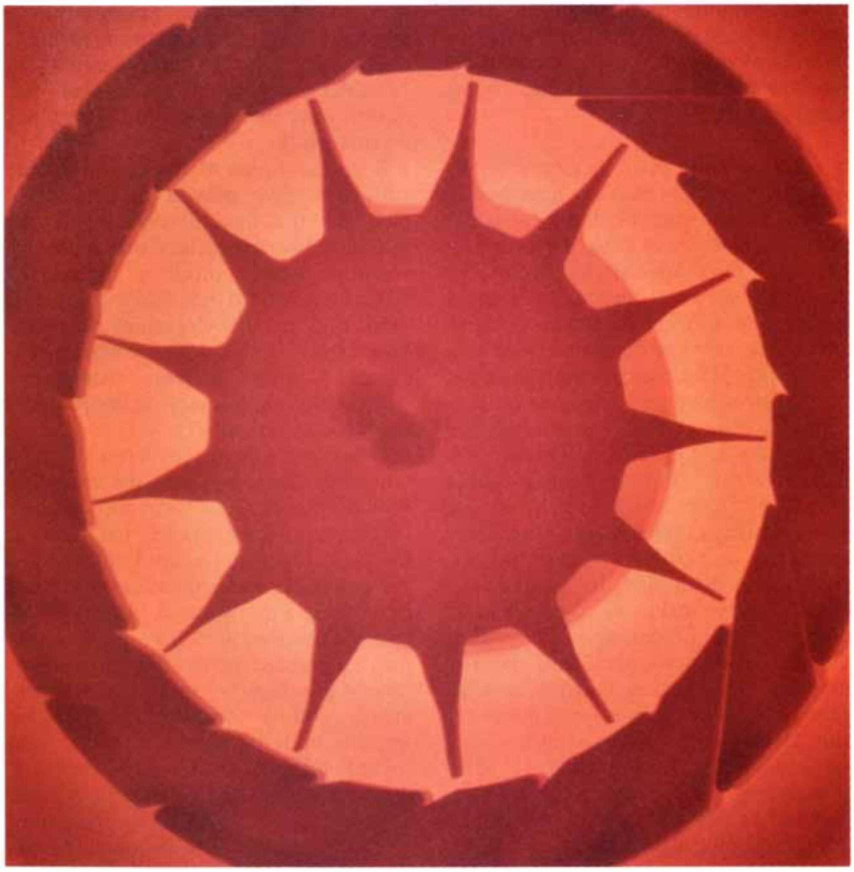
Another area of growth is in piezoelectric ceramics. I shall mention just two interesting new applications. The first is a high-precision ink-jet printing head. The head consists of hundreds of tiny piezoelectric inkwells. By selectively applying a voltage to the inkwells, they can be made to contract suddenly, thereby "squirting" their ink onto paper in patterns corresponding to characters. Fine detail and coloring are possible with such a printing head, and it requires very little space and lower drive voltages compared with other heads.

Direct-drive motors can also be constructed from piezoelectric ceramics by converting the dilation of the ceramic when it is exposed to an electric field into translational or rotational motion. Such motors are compact, lightweight and simple because they require no wiring for field winding. They can stop and start without slippage and also provide high torque at low speeds: kilogram loads can be moved slowly and precisely.

One such motor, developed by the Shinsei Electric Industrial Company, Ltd., in Japan, is a linear direct-drive motor. The mass to be moved is placed on a fixed piezoelectric-ceramic rail. Application of a high-frequency voltage to the rail produces "ripples" on its surface that can drive the mass forward or backward on the rail. Hundreds of applications in machines, appliances and consumer products are being considered for these motors.

In many ways ceramics represent man's greatest opportunity to engineer economically a made-to-order material virtually from scratch. Physical properties of the material can be changed or enhanced by minute changes in composition and grain orientation, by combining different ceramics into a composite and by eliminating (or purposely creating) voids. Ceramists are gaining the necessary fine control over composition and microstructure by crystallizing glasses, by starting with extremely fine powders of high chemical purity and by chemically packing the powders tightly together. Furthermore, the elements that go into ceramics are among the most abundant elements on the earth. The raw materials for ceramics are therefore likely to remain far cheaper than the raw materials for the closest substitute materials, which generally are special metal alloys containing expensive—and relatively rare—elements such as cobalt, tungsten, columbium and chromium.

Although the susceptibility of ceramics to slight imperfections during processing means it is not easy to make and shape ceramics of high enough quality at a low enough cost, the potential value that ceramic materials gain with each increment in purity and homogeneity makes it worthwhile to continue exploring new ways to reach virtual perfection in processing. Attaining perfection in the laboratory, however, is not enough. Successful laboratory processes must then be converted to industrial-scale processes without relinquishing the exquisite control of composition and microstructure. The search for delicate processing techniques that can be scaled up to commercial proportions makes advanced-ceramics processing one of the great engineering challenges for the rest of this century.



CERAMIC ROTOR (*star-shaped object*) improves the efficiency of a new gas-turbine engine by enabling it to operate at temperatures where a metal rotor would fail. The engine was developed by the Garrett Turbine Engine Company and the Ford Motor Company for the U.S. Department of Energy and the National Aeronautics and Space Administration.

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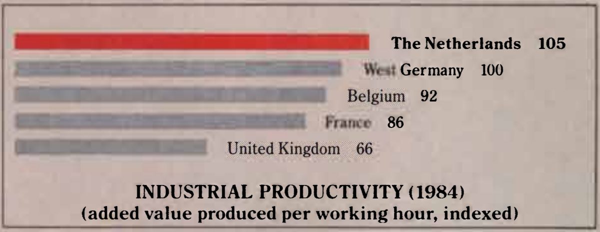

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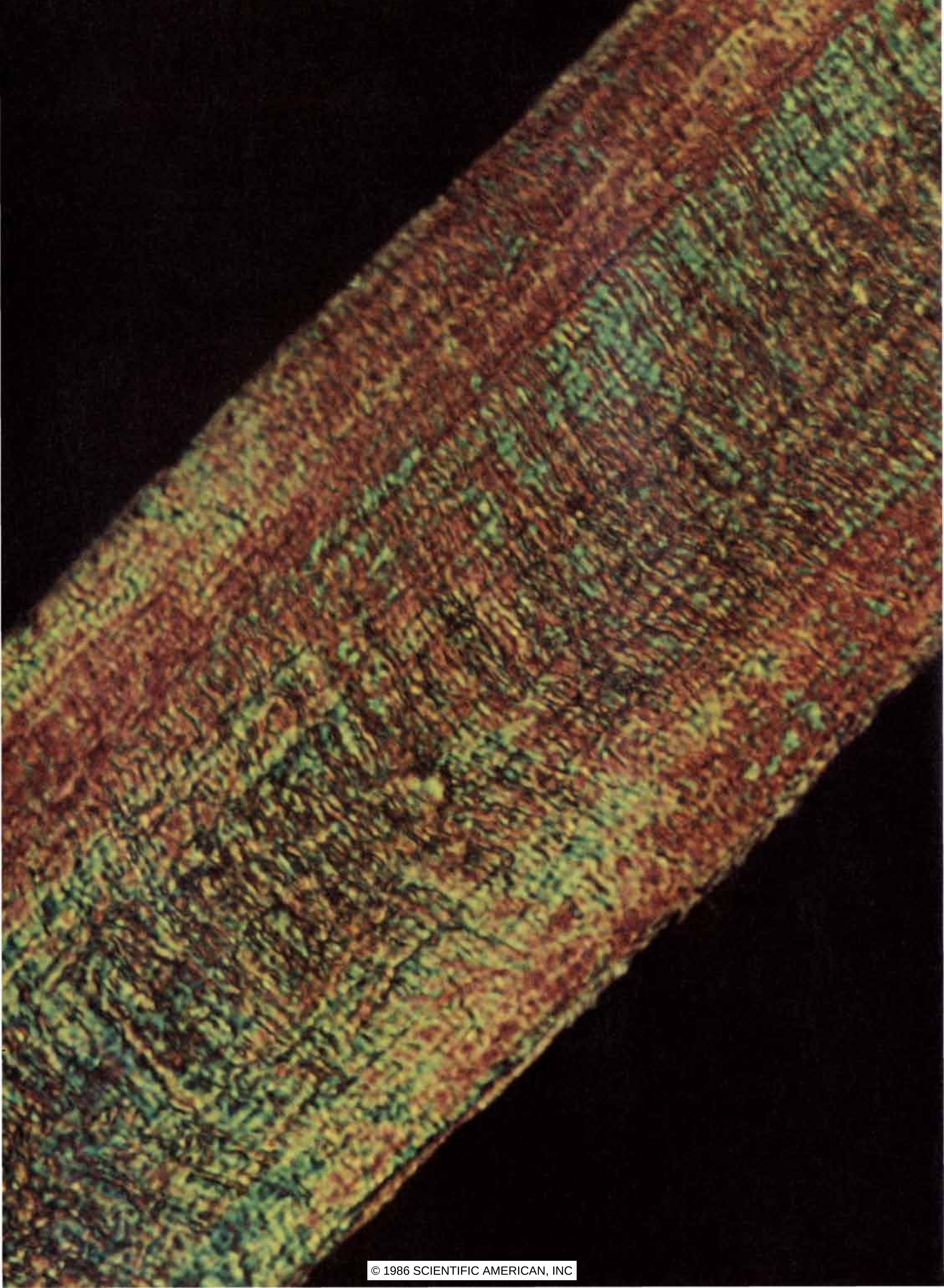


Advanced Polymers

Polymers with unprecedented qualities are emerging from advances in synthesis and from processing methods based on new knowledge about the relations between structure and properties in polymers

by Eric Baer

Three decades ago most polymers were limited to specialized service in products such as fibers, films and coatings—or to their familiar role as light-duty, inexpensive plastic materials. In the demanding environment of high technology traditional materials held sway. Now some polymers are replacing aluminum and other structural metals in applications exposing them to high temperatures and mechanical stress; others may eventually substitute for traditional materials in electronic and optical communication and computation. Each new role testifies to the enormous degree of control that can be exerted over the properties of polymers.

Polymer science gains its power from the infinite versatility of synthetic polymers. Not only the bulk materials but also their basic constituents, polymer molecules, are tailor-made. The polymer molecule is built from smaller molecular units known as monomers, repeated hundreds or thousands of times in a chainlike structure. The choice of monomers and the way they are assembled shape the properties of the bulk material.

The polymer can also be tailored on a larger scale. Like a metal or a composite, it can be given a microstructure—for example, an oriented arrangement of molecules or a controlled array of regions that differ in composition. Thus the made-to-order products of polymer chemistry can be further shaped to human wants through polymer processing.

The first level at which workers learned to influence the properties of polymeric materials, and still one of the most fruitful domains for such control, is that of molecular design. Four factors inherent in the design of the macromolecules, or polymer chains, critically affect the physical behavior of the bulk material. One factor is the average length of the chains, which for each polymer must be above a certain threshold if the material is to have a useful measure of stiffness and toughness. The other three are the strength of the forces among polymer chains, the regularity with which the chains can pack together and the stiffness of the individual chains.

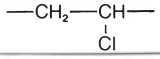
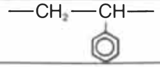
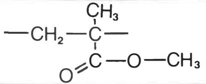
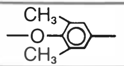
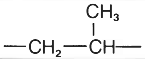
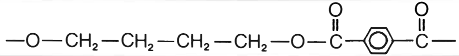
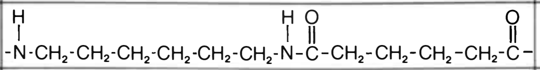
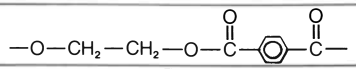
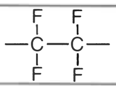
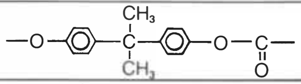
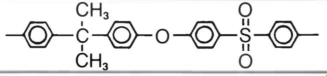
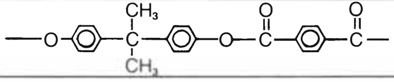
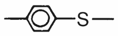
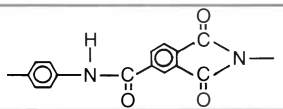
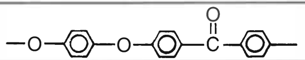
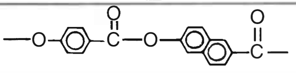
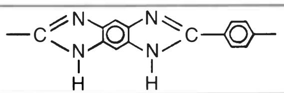
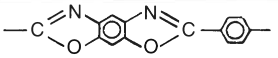
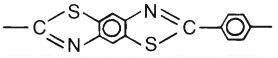
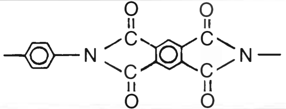
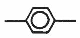
The strongest intermolecular forces arise when the chains are designed to cross-link, or form chemical bonds with one another, a step that often occurs as the polymer is heated during its final processing. Because cross-linking locks the polymer chains into a three-dimensional lattice, such polymers cannot be reshaped with heat. Stiff plastics of this type are called thermosets. Thermosets such as phenolics were among the first polymers to show high strength and temperature resistance. Rubbers, both synthetic and natural, also develop cross-links when they are thermally cured. Their cross-linked structure enables rubbers to withstand high temperature and repeated stress without distorting permanently. In contrast, many advanced polymers of today, like the familiar plastics of consumer goods, are thermoplastics: materials that soften when they are reheated. The polymer chains in a thermoplastic remain chemically distinct, although they can interact in various ways.

Strong attractions among molecules, for example, increase a thermoplastic's toughness and resistance to solvents, and polymer scientists often design the molecular chains to increase those attractions. In pure polystyrene, which consists of a backbone of covalently bonded carbon atoms surrounded by hydrogen atoms and bearing a six-carbon benzene ring on every second backbone atom, the molecule is nonpolar: it lacks localized concentrations of positive and negative charge, which could give rise to electrostatic forces among the chains. Only the feeble intermolecular attractions known as van der Waals forces draw the chains together. Hence polystyrene is vulnerable to organic solvents and softens at a fairly low temperature, about 100 degrees Celsius.

If more polar monomers—monomers with a less symmetric distribution of charge—are placed along the polymer chain, electrostatic attraction will contribute to the intermolecular forces. For example, the nonpolar styrene monomers can be interspersed with more polar acrylonitrile monomers, a step that increases the cohesion of the molecules and hence the solvent resistance of the bulk material. The copolymerization of styrene and acrylonitrile is now routine, and many other commercial polymers similarly incorporate two or more different monomer building blocks.

In certain copolymers the monomers are not placed randomly along

EXPERIMENTAL HIGH-PERFORMANCE FIBER, shown in polarized light, reveals the oriented structure that gives it great tensile strength and stiffness. The polymer from which the fiber was made is liquid-crystalline: when it is in a liquid phase (molten in this case), its rigid rodlike molecules can be aligned easily. In fibers spun from the melt the molecules line up nearly parallel to the fiber axis, yielding the fibrillar structure visible in the micrograph. The transverse banding is believed to arise from a periodic meander in the molecular orientation; in fully oriented fibers of the same polymer the banding does not appear. The experimental fibers were developed by the Celanese Research Company. Linda C. Sawyer of Celanese has analyzed their structure and is the source of the image.

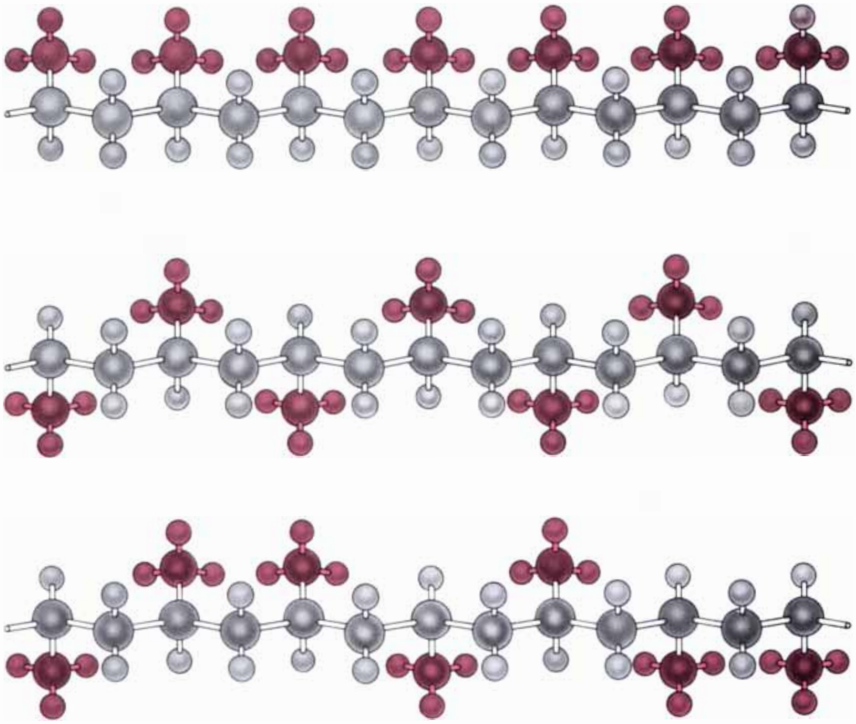
POLYMER	CHAIN UNIT	MELTING TEMPERATURE	GLASS-TRANSITION TEMPERATURE
POLYVINYLCHLORIDE	 $-CH_2-\underset{Cl}{CH}-$	—	82
POLYSTYRENE, ATACTIC		—	100
POLYMETHYL METHACRYLATE, ATACTIC		—	105
POLY (2,2′-DIMETHYL PHENYLENE OXIDE) (PPO)		—	135
POLYETHYLENE, LINEAR	$-CH_2-CH_2-$	138	−110
POLYPROPYLENE, ISOTACTIC	 $-CH_2-\overset{CH_3}{CH}-$	165	−10
POLYOXYMETHYLENE	$-CH_2-O-$	180	−85
POLYBUTYLENE TEREPHTHALATE		240	17
POLYHEXAMETHYLENE ADIPAMIDE	 $-\overset{H}{N}-CH_2-CH_2-CH_2-CH_2-CH_2-CH_2-\overset{H}{N}-\overset{O}{C}-CH_2-CH_2-CH_2-CH_2-\overset{O}{C}-$	265	50
POLYETHYLENE TEREPHTHALATE		265	70
POLYTETRAFLUOROETHYLENE	 $-\overset{F}{\underset{F}{C}}-\overset{F}{\underset{F}{C}}-$	327	−150
POLY (4,4′-ISOPROPYLIDENE DIPHENYLENE CARBONATE)		—	149
POLYETHER SULFONE		—	190
POLYARYLATE		—	190
POLYPHENYLENE SULFIDE		285	185
POLYAMIDE-IMIDE		—	MORE THAN 290
POLYETHERETHERKETONE		334	143
AROMATIC COPOLYESTER OF 6,2-HYDROXYNAPHTHOIC ACID AND 1,4-HYDROXYBENZOIC ACID		WIDE RANGE	
POLY (PARA PHENYLENE BENZOBISIMIDAZOLE) (PBI)		DECOMPOSITION TEMPERATURE	MORE THAN 400
POLY (PARA PHENYLENE BENZOBISOXAZOLE) (PBO)			MORE THAN 400
POLY (PARA PHENYLENE BENZOBISTHIAZOLE) (PBT)			MORE THAN 400
POLYIMIDE			MORE THAN 400
POLYPHENYL			MORE THAN 530

SAMPLER OF POLYMERS shows in each case the basic chemical unit, the monomer, that is repeated hundreds or thousands of times in the complete polymer chain. The table indicates resistance to heat in degrees Celsius. Polymers for which only a glass-transition temperature is given are amorphous, or glassy; they are stiff below that temperature and highly viscous above it. For semicrystalline polymers the table shows both a melting temperature, at which the crystalline regions become fluid, and a glass-transition temperature, which applies to the amorphous regions surrounding the crystalline areas. A rough correlation prevails between heat resistance and the presence of aromatic groups (*shown as hexagons*) and other ring-shaped stiffening elements in the backbone of the polymer molecule. Many advanced polymers are blends that combine several of the materials shown in the table.

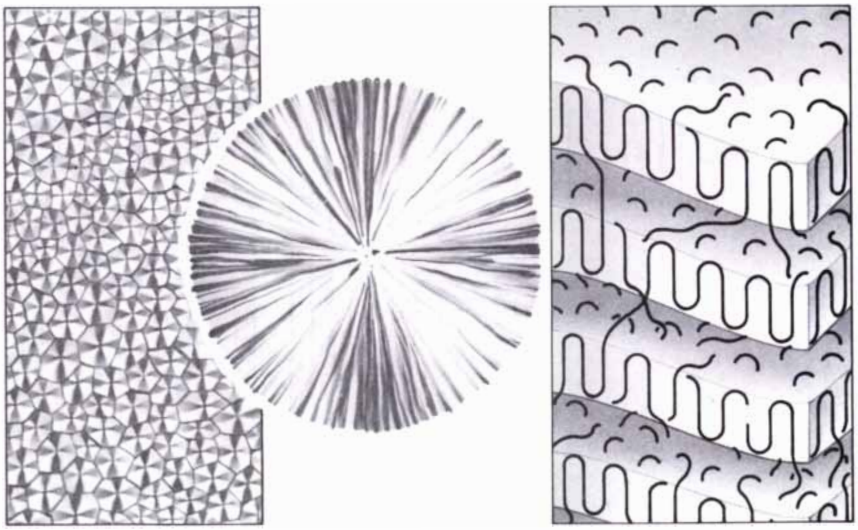
the polymer chain, as they are in styrene-acrylonitrile copolymer, but are grouped in blocks, in which a single kind of monomer is repeated without interruption. When the different polymers represented by the blocks are immiscible—mutually insoluble, like oil and water—blocks lying on different macromolecules but made up of the same monomer tend to coalesce. The bulk polymer thus becomes segregated into minute domains representing different polymers; by varying the length of the blocks one can control the domain size and shape. The best-known example of a block polymer consists of alternating blocks of styrene and butadiene. In polymeric form butadiene is an elastomer, or a synthetic rubber. When styrene is the dominant constituent, the bulk styrene-butadiene copolymer retains most of the stiffness of polystyrene but is toughened by the tiny rubber particles dispersed in the continuous matrix of polystyrene.

The shape of the polymer molecule as well as its chemical makeup influences the properties of the bulk material. In many polymers the carbon or other atoms that participate in the backbone also bear side groups. The aromatic, or benzene, rings on polystyrene are one example, and in polypropylene a methyl group (a carbon surrounded by three hydrogens) is attached to every second carbon in the backbone. About 30 years ago investigators found that by means of certain specialized catalysts propylene monomers can be made to assemble so that the methyl groups are disposed regularly around the polypropylene chain. All of them can end up on one side of the chain, or they can alternate sides. Such regularity is called tacticity.

Tacticity influences the large-scale packing of polymer chains bearing side groups. An atactic polymer such as polystyrene, whose benzene groups extend in random directions from the chain, is amorphous: its molecules are loosely tangled and have no long-range order. In a tactic polymer, in contrast, the regularity of the side groups enables the chains to nest closely, forming regions in which they are densely and regularly packed in a complex crystalline array. Such partially crystalline character, which is also found in many polymers that lack bulky side groups, generally increases the material's density, stiffness and resistance to solvents and heat. In the case of polypropylene the atactic variety is a highly viscous liquid at room temperature. Semicrystalline polypropylene, the commonest tactic polymer in commercial use, is denser and stiff-



TACTICITY, or the orderly placement of side groups, can distinguish chemically identical polymers. The three polypropylene chains vary only in that the upper two have been constructed so that the methyl group (three hydrogen atoms bound to a carbon atom) attached to every other carbon in the polymer backbone has a predictable orientation: it is always either on the same side of the polymer chain (*top*) or on alternating sides (*middle*). Such three-dimensional regularity enables the molecules of a tactic polymer to pack together closely and regularly, giving the bulk material a partially crystalline character. In contrast, an atactic polymer, exemplified by the form of polypropylene in which the orientation of the methyl groups is random (*bottom*), is amorphous. Because the polymer chains are packed more densely in the crystalline regions, tactic forms of polypropylene are stiffer and more resistant to heat than atactic polypropylene is. The diagrams simplify the complex geometry of the tactic polypropylene chains, which in fact form helixes.



MICROSTRUCTURE OF A SEMICRYSTALLINE POLYMER such as polyethylene is shown at three levels of detail. Under polarized light such polymers are usually found to be made up of closely packed spherulites: sunburstlike structures formed as the polymer solidified and crystal growth began at nucleation points and radiated outward. Spherulites commonly grow to diameters of between tens and hundreds of micrometers (millionths of a meter). On a finer scale each spherulite is a radial assemblage of narrow crystalline plates oriented in many different planes. Within each of the lamellae, or plates, tightly packed polymer chains fold back and forth between two boundaries; amorphous regions where molecules are tangled and disarranged fill spaces between lamellae.

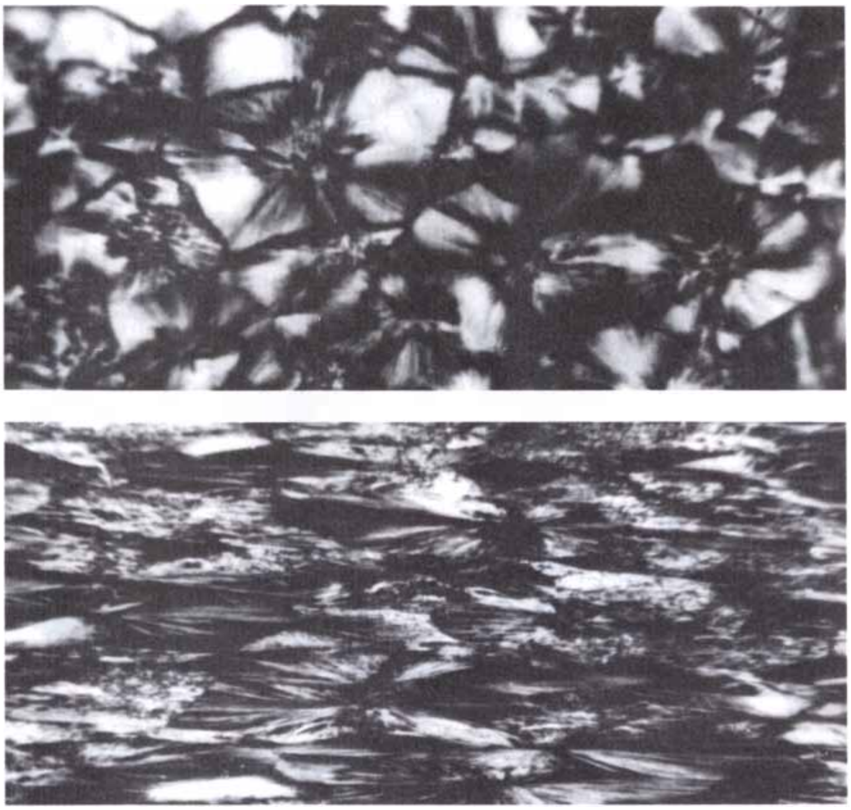
er. It melts at 165 degrees C. and is often found in heat-resistant plastic products.

Unless a polymer such as polypropylene is reinforced with another material, it can be stiffened only by crystallization, because the polymer chains are intrinsically flexible. In the polypropylene backbone, as in that of many other polymers, adjacent atoms are joined by a single covalent bond. Like the coupling joining railroad cars, the single bond allows pivoting, and so the chain can fold, coil and twist. In recent years polymer chemists have introduced molecular designs in which the chain is inherently more rigid and straight. Aromatic groups incorporated into the chain serve as the stiffening elements. They contain double bonds, which are resistant to bending, and in a phenomenon known as resonance those bonds impart double-bond character to adjacent single bonds in the backbone. When enough aromatic groups are placed in the polymer chain, the molecule comes to resemble a rigid rod.

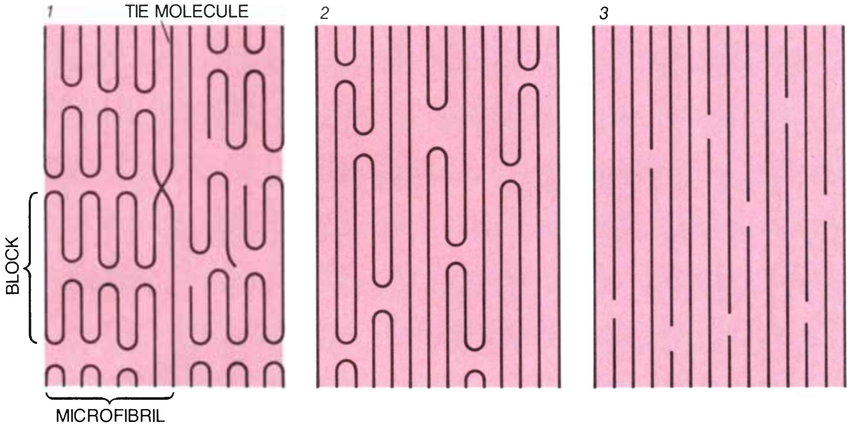
An aromatic polymer-chain design yields a double boon. The rigidity of the individual molecules stiffens the bulk polymer. Their rodlike character can also cause them to become aligned under certain conditions. Specifically, certain rigid-rod polymers are liquid-crystalline: in solution or in the melt the macromolecules can spontaneously line up, like logs in a jam, forming regions in which most of the molecules are oriented in one or perhaps two directions. The extent of the ordered, crystal-like regions can increase under certain conditions of flow, such as passage through a spinneret. Hence it is easy to spin a liquid crystal into fibers in which many of the polymer chains are oriented along the axis of the fiber.

When such a fiber is tensed, the links that are stressed are not weak intermolecular attractions but covalent carbon-carbon bonds, the same links that account for the hardness of diamond. Aramid fibers, commercial fibers spun from a liquid-crystalline phase, have a tensile strength comparable to that of steel. In their solid phase liquid-crystalline polymers also benefit from chain alignment. The oriented regions that formed in the liquid phase then act as reinforcing elements, greatly increasing the stiffness of the material. Such polymers have relatively high softening points and great resistance to most solvents.

Certain experimental polymers of very different design also show liquid-crystalline character. In such polymers the main chain is flexible, but it bears long side chains containing aromatic



DEFORMATION OF POLYPROPYLENE transforms its microstructure. A micrograph made in polarized light shows packed spherulites within a sample of the undeformed polymer (*top*). After the material was simultaneously compressed in one dimension and extended to about two and a half times its original size in the other two dimensions, the spherulites were flattened into disks (*bottom*). X-ray analysis showed the lamellae making up the spherulites had rotated into the plane of the sheet and broken up into crystalline blocks connected by a web of amorphous molecules. The planar structure of blocks and tie molecules, oriented along the axes of extension, is believed to account for the much greater strength and toughness of a deformed sheet compared with the same thickness of the undeformed polymer. The work was done in the author's laboratory, the Case Center for Applied Polymer Research, in collaboration with the Bethlehem Steel Corporation.



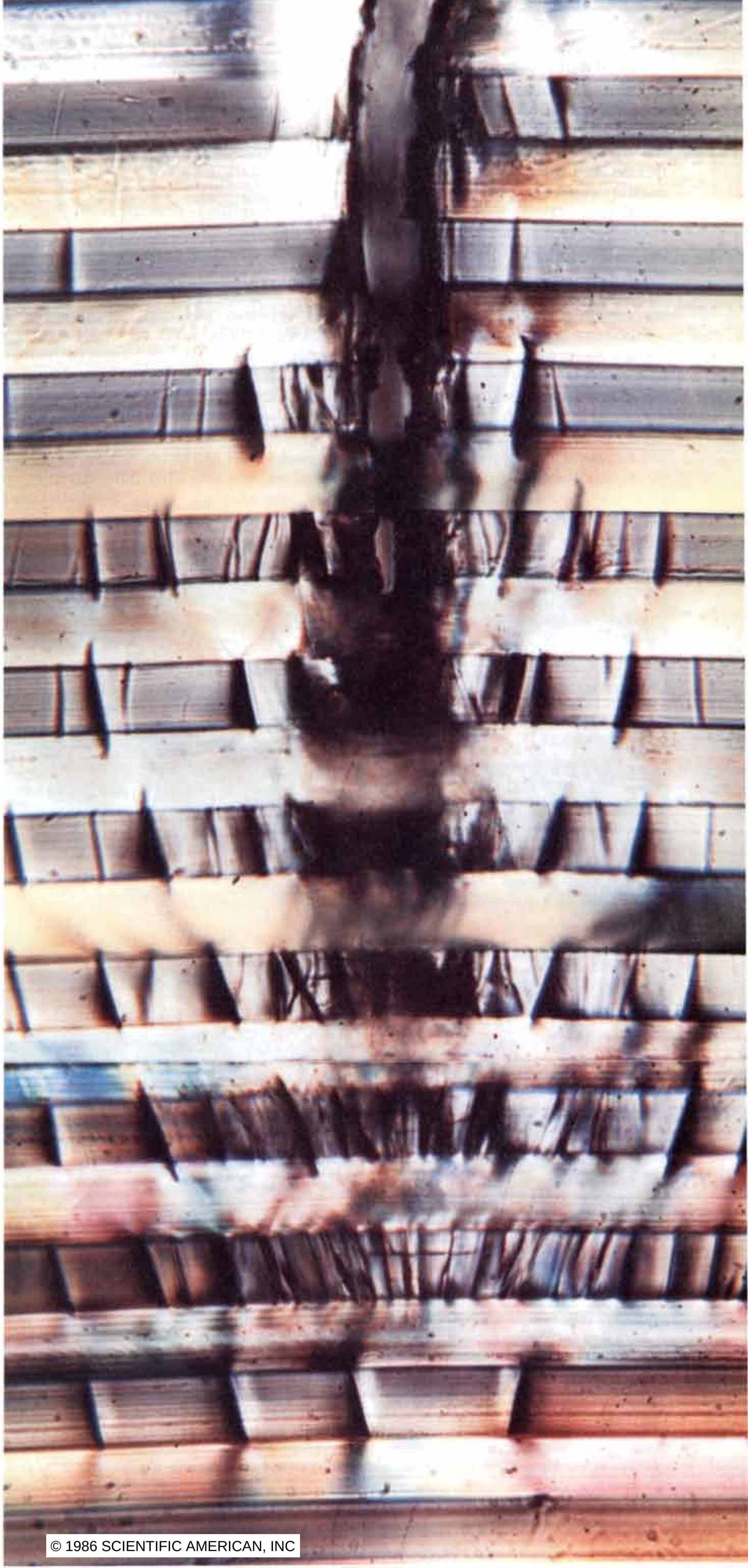
ALIGNMENT OF POLYMER CHAINS lends tensile strength to a fiber drawn from a semicrystalline polymer. During the initial stretching the crystalline lamellae in the polymer break up into smaller blocks of folded chains, which line up end to end to form numerous distinct microfibrils (*1*). The blocks are linked by extended tie molecules, which strengthen the microfibrils. More extensive stretching of the polymer partially unfolds the blocks and causes the microfibrils to merge (*2*). The greater number of molecules that are extended along the axis of the fiber further strengthen it. In an ideal morphology all the polymer chains would lie along the axis of the fiber (*3*), and the fiber would benefit fully from the great longitudinal strength of the polymer macromolecules.

groups. The side chains act as rigid rods and interdigitate to form oriented regions, whereas the main chains flexibly interconnect the rods.

By varying the characteristics of polymer chains one can cause them to form a microstructure that is amorphous or semicrystalline, uniform or disrupted by regions of differing composition or molecular orientation. Polymer scientists and engineers have not been content, however, to devise molecules that spontaneously assemble into a favorable microstructure. In many efforts to improve a polymer the synthesized molecule is only a starting point. The polymer is then subjected to processing that transforms its structure and properties.

A kind of processing that is now routine is blending, a strategy that was first applied to amorphous polymers such as polystyrene, polyvinyl chloride and polymethyl methacrylate, an acrylic. Because they are not crystalline, such polymers have no melting point. Above a critical temperature known as the glass-transition temperature, however, they become soft and rubbery. Amorphous polymers are serviceable only at lower temperatures, where their molecular structure is frozen and the material is glasslike. Most amorphous polymers are brittle below their glass-transition temperature, although there are notable exceptions, such as polycarbonate, a tough material found in protective helmets.

To increase the toughness of a brittle amorphous plastic it can be combined with another polymer, usually an elastomer. Most blends combine immiscible components, and so the

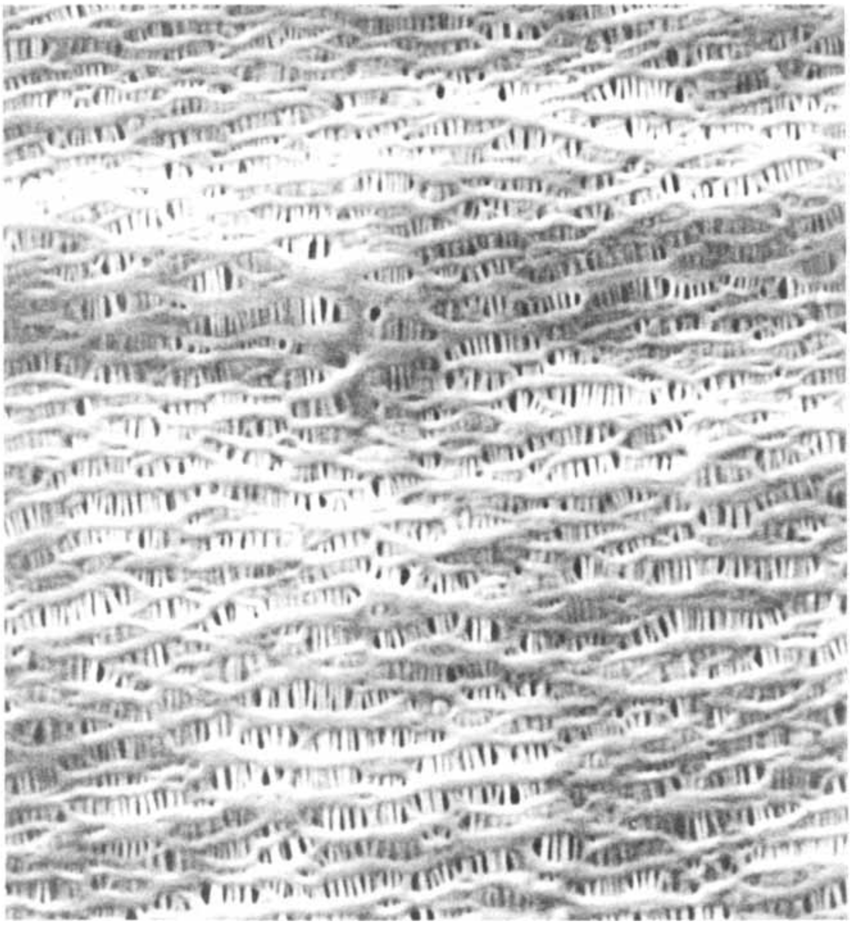


SYNERGY OF PROPERTIES in a sheet consisting of alternating layers of two different polymers is suggested by its response to a fracture (the dark zone extending from the top of the image). The layers are 10 micrometers thick; the darker ones are made of styrene-acrylonitrile copolymer, a stiff but relatively brittle material, and the lighter layers are polycarbonate, which is tough and ductile. The brittle layers readily crazed (formed tiny cracks), enabling the fracture to grow, but the ductile regions formed shear bands: regions of ductile deformation that are visible as bands of color in this micrograph, made in polarized light. The formation of the shear bands absorbed energy, blunting the tip of the crack and ultimately stopping it. Thus the sheet is toughened by the layers of polycarbonate, while the layers of styrene-acrylonitrile copolymer stiffen it. The sheet is a product of Dow Chemical Company; the image was made in the laboratory of the author in collaboration with Dow.

material that results contains tiny particles of one polymer in a matrix of the other. Controlled mixing and cooling of the blend makes it possible to form the particles in the optimum concentration and range of sizes. In a glassy plastic combined with a relatively small proportion of an elastomer the rubber particles toughen the material by enabling it to absorb energy more efficiently as it is fractured. Its resistance to crack propagation is thereby increased substantially.

Recently a new class of immiscible blends have been developed: the so-called high-performance blends, incorporating several components in amounts that are more or less equal. With many such blends the object is not so much to relieve brittleness as to improve other qualities. A promising example combines polycarbonate with polybutylene terephthalate. Because neither polymer is the dominant component, the two phases coexist in an intricate interpenetrating network. The blend's resistance to heat and solvents is higher than that of pure polycarbonate, and its durability makes it a candidate for the replacement of metal in automotive components such as bumpers.

Few alloys, or miscible blends, have been developed; the best-known is an alloy of polystyrene and another amorphous polymer, polyphenylene oxide (PPO). The two polymers can mix molecule by molecule to form a solid solution; in approximately equal parts they produce a ductile material. Pure polystyrene crazes when it is stressed, developing a network of tiny cracks that leads to relatively brittle failure, but the alloy deforms ductilely, developing shear bands: zones where the material is stretched and thinned, angled about 45 degrees to the direction of stress. It appears that the ductile behavior of the polystyrene/PPO blend stems from the strong affinity between molecules of those two polymers—the same factor that accounts for their miscibility.



MICROPOROUS MEMBRANE was made by repeatedly stretching polypropylene film at high and low temperatures. The process has created minute, parallel rips in the film, spanned by microfibers that define an average pore size of several hundred angstrom units (one angstrom is 10^{-10} meter). Because polypropylene repels water, such a membrane normally is watertight but is permeable to gases and other substances—qualities that suit it for use in blood-oxygenation devices and drug-delivery systems. If the membrane is treated chemically to make it wettable, it can also serve as a microfilter capable of separating microorganisms such as bacteria from water. The scanning electron micrograph shows Celgard, a product of the Celanese Corporation, and was provided by Celanese Separations Products.

Unlike amorphous polymers, semicrystalline ones are inherently tough. Because they consist of crystalline regions interspersed with amorphous material, they are characterized by both a glass-transition temperature, which is relevant to the amorphous phase, and a melting point, at which the crystalline regions become fluid. Most of the semicrystalline materials in wide use have glass-transition temperatures below room temperature; that of polyethylene is −110 degrees C. and that of nylon is about zero degrees. When nylon is thoroughly dry, its glass-transition temperature is higher, but nylon spontaneously absorbs water molecules that lower the glass transition by acting as a plasticizing agent, in effect lubricating the chains in the amorphous region. The rubbery condition of the amorphous phase toughens nylon and other semicrystalline polymers.

Nevertheless, it has recently been found that blending a semicrystalline polymer with an elastomer toughens it still further. Spherical rubber inclusions efficiently dispersed through a nylon, polypropylene or polyoxymethylene matrix yield a so-called supertough blend, which is usually intended for engineering uses.

The newest class of blends resemble composites reinforced with fibers; they combine a flexible-chain polymer such as nylon with a rigid-rod polymer. The rigid-rod component, dispersed in the flexible-chain matrix, acts as a molecular reinforcing fiber. Such "molecular composites" exhibit great stiffness and resistance to heat and chemicals, characteristics that may suit them for use as substitutes for metal in certain components of aircraft structures and engines.

Blending makes it possible to combine the good properties of several polymers; other methods of processing enhance the strength of a single polymer. If the bulk material is to benefit fully from the longitudinal strength of the polymer molecules, they must have a common orientation. Many rigid-rod polymers are readily oriented, but it is also possible to align the chains in a conventional flexible-chain polymer through appropriate processing. The product is usually a fiber in which many of the ordinarily folded or coiled polymer chains are extended along the fiber axis, lending it great strength and stiffness.

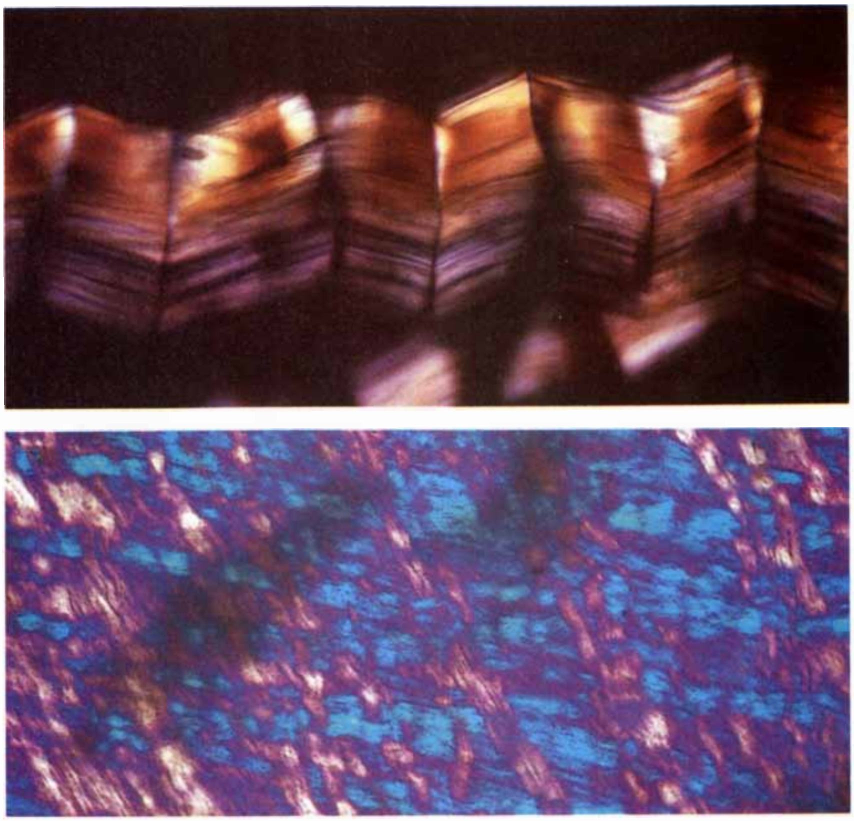
Oriented fibers made from semicrystalline polymers such as nylon are the mainstay of the synthetic-fibers industry. Recently even stronger fibers with a higher degree of orientation have been produced from other semicrystalline polymers, notably polyethylene. To understand how polyethylene, the soft plastic of squeeze bottles, can without chemical alteration be transformed into fibers with a tensile strength greater than that of an equivalent weight of steel one must follow the underlying changes in microstructure. The microstructure of polyethylene, like that of most semicrystalline polymers, is dominated by spherulites: structures resembling sunbursts, made up of crystalline plates radiating from a common center. Within each of the lamellae, or plates, the polymer chains fold back and forth between two planes; filling the spaces between the lamellae are amorphous regions.

As a semicrystalline polymer is drawn into a fibril the spherulites pull apart and the lamellae break up into small blocks of folded chains. The chief structural elements of the fibril are microfibrils, in which crystalline blocks are lined up end to end. The blocks are separated by less-ordered regions but linked by tie molecules extending from block to block.

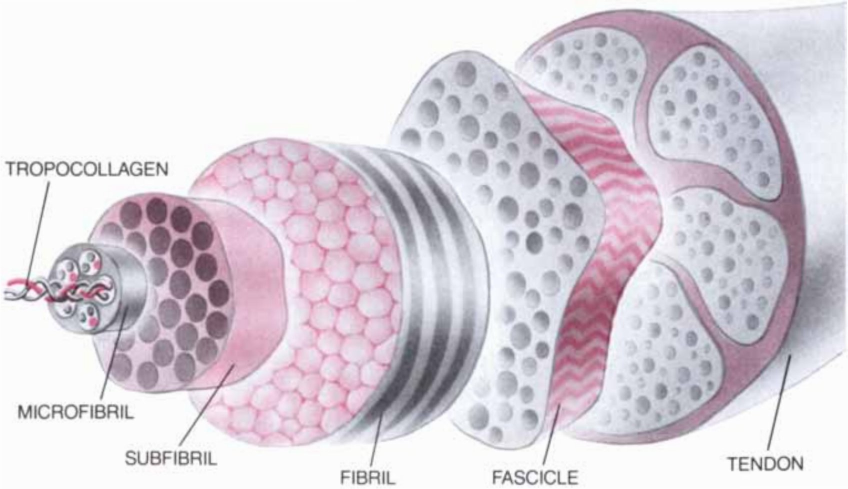
Recently certain processing conditions have been found that can increase the degree of extension and orientation of the macromolecules. Extrusion or extensive slow drawing at a temperature near the melting point of the polymer are ways to achieve the orientation; in another strategy the polymer is treated with a solvent to form a gel, from which the oriented fibers are spun. In the gel the network of macromolecules making up the material is expanded, reducing its resistance to spinning.

It is also possible to orient a semicrystalline polymer in two dimensions rather than one, resulting in polymer sheet or film with increased strength and toughness. Rolling the polymer in alternating perpendicular directions can produce the needed deformation. Another strategy is solid-state extrusion: a tube of polymer is forced through a die that simultaneously expands the tube and compresses its wall, deforming it longitudinally as well as circumferentially. The sheet that results when the expanded cylinder is cut open and flattened has about three times the tensile strength and about nine times the toughness of unoriented polypropylene sheet.

At Case Western Reserve University



BIOLOGICAL POLYMERS have an architecture that is precisely matched to the stresses they experience. The longitudinal strength of tendon is the product of bundled fibrils of collagen, a polymer, oriented along the axis of the tendon (*top*). Polarized light reveals the crimping of the fibrils, which makes them elastic. The wall of the intestine is also reinforced by crimped collagen fibrils, which are set in interwoven arrays (*bottom*). Each set of parallel fibrils forms an angle of about 30 degrees with the long axis of the intestine. (In this micrograph the axis runs diagonally from the upper left to the lower right.) The arrangement combines reinforcement with the needed elasticity. When the wall of the intestine is stretched, the fibrils uncrimp and the angles between the arrays change. Ultimately, however, the collagen fabric becomes inextensible, protecting the intestine from rupture. The micrographs were made by the author and his colleagues.



HIERARCHY of structural units in tendon begins with the tropocollagen molecule, a triple helix of polymeric protein chains, and builds through microfibrils, subfibrils, fibrils (which are crimped when they are not under tension) and fascicles to the tendon itself. The hierarchical organization of tendon is responsible for its toughness. The separate structural units can fail independently when the tendon is subjected to excessive stress, absorbing energy locally and in that way protecting the tendon as a whole from rupture.

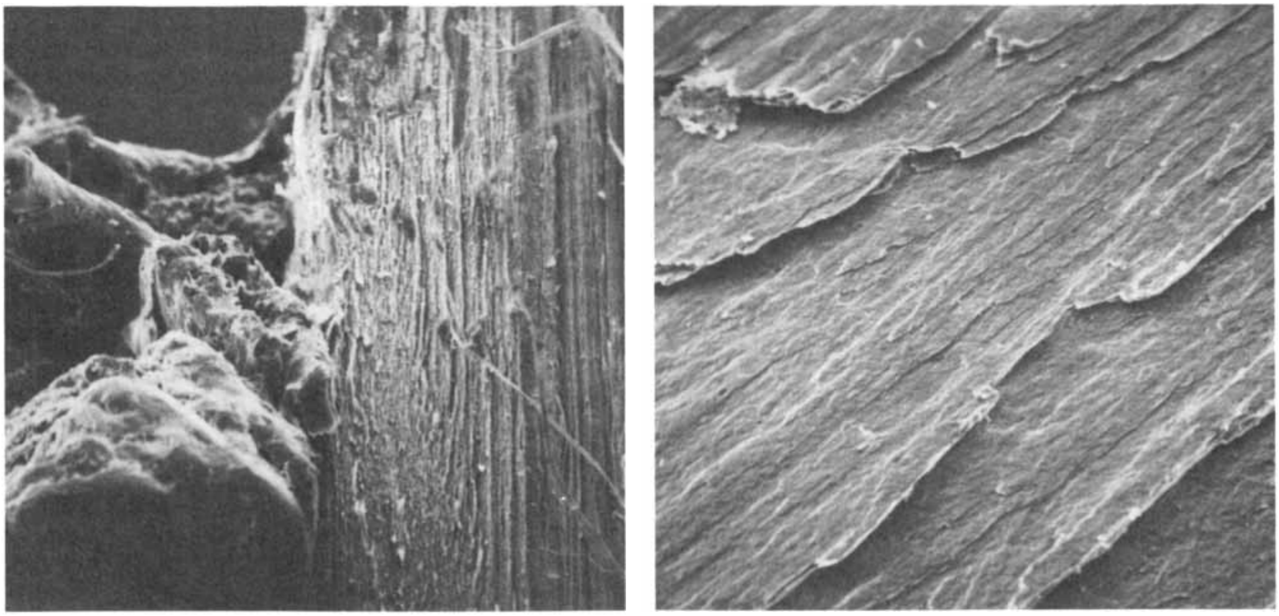
in the Center for Applied Polymer Research my colleagues and I have analyzed the microstructural changes that underlie the increase in strength and toughness. Under the light microscope we followed changes in the shape of the crystalline spherulites that occur as polypropylene is deformed in two dimensions; X-ray-diffraction patterns enabled us to trace the concomitant changes in molecular orientation. We found that as the spherulites are flattened the crystalline lamellae rotate into the plane of the sheet. They break up into smaller crystalline blocks, which in the fully deformed sheet are embedded in an amorphous web of polymer chains that have become oriented in the directions of deformation. The oriented network of crystallites and tie molecules strengthens the deformed sheet.

Recent advances in polymer processing have made it possible to create structures that are less intimately related to molecular characteristics than the structures discussed so far. Instead of blending several polymers, for example, it is possible to extrude them simultaneously to form a structure made up of alternating layers of different polymers, each layer about 10 micrometers thick. The full thickness of the material may include hundreds or thousands of layers; if one component is stiff but brittle and the other is rubbery, the bulk material may be both stiff and tough.

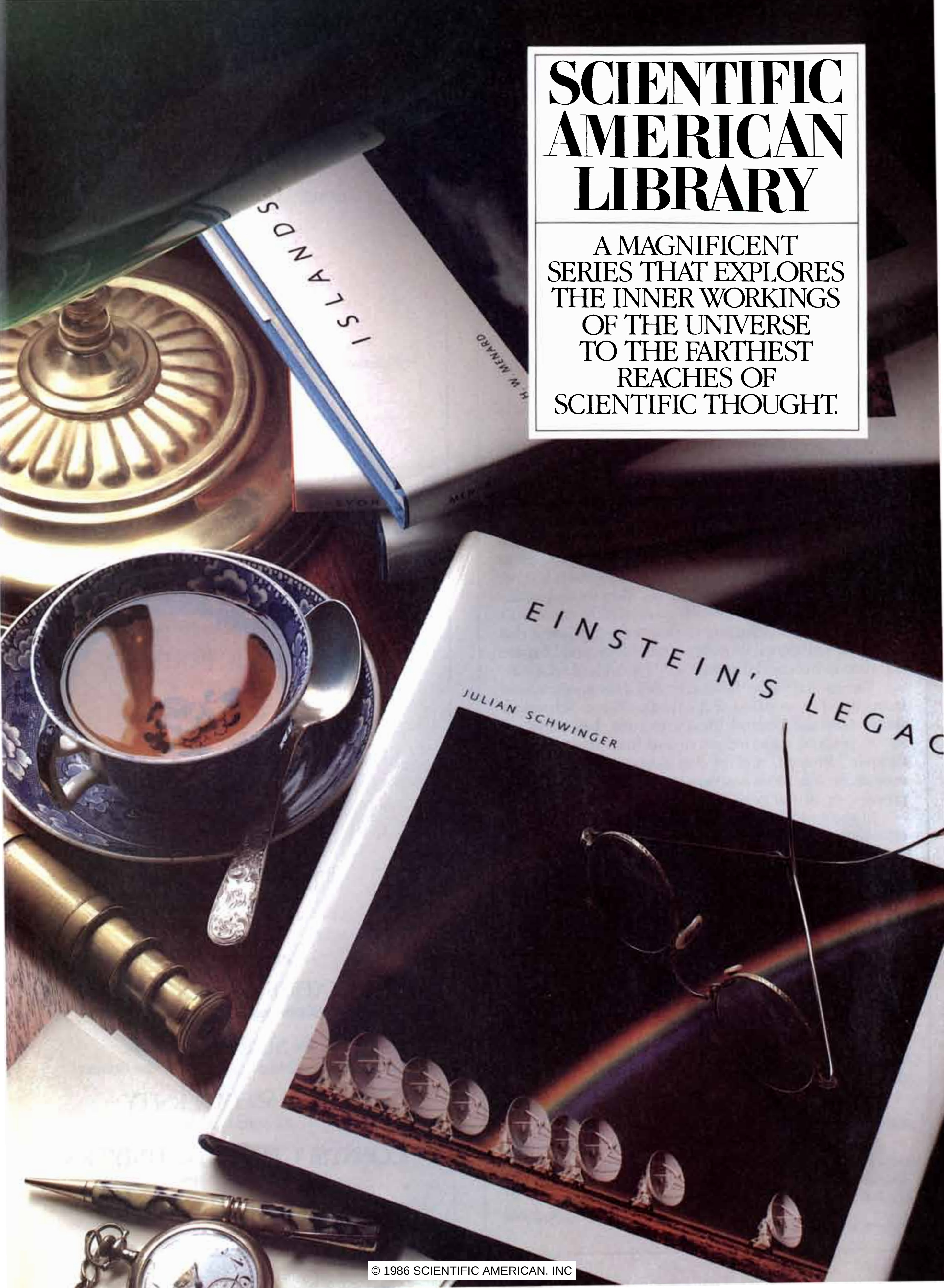
Such imposed structure is also crucial to the performance of polymeric membranes, a class of materials that have given rise to new industrial processes, medical devices and consumer goods. Some membranes are microporous, or pierced with holes fine enough to prevent the passage of a bacterium. The holes are often "microtears": small rips made in the plastic film by stretching it. Some membranes of this kind are used for microfiltration. Others, because they are made from a hydrophobic (water-repellent) polymer, allow the passage of certain liquids and gases but not of water or aqueous solutions; they find applications in "breathable" waterproof clothing, blood-oxygenation devices and drug-delivery systems.

Most membranes are nonporous; molecular dynamics controls their permeability. The electronic structure of the polymer may foster the passage of particular ions, making it valuable in electrodialysis: the use of an electric field to draw ions across a membrane. Still others are permeable only to water or are selectively permeable to gases. In their intended uses—desalting seawater by reverse osmosis or separating oxygen from air—such membranes must often withstand a high-pressure flow of liquid or gas. At the same time the membrane must be thin enough to be adequately permeable. Hence it requires a mechanical support, a need that can be answered by fabricating the membrane as a thin, unbroken layer of polymer backed by a thicker porous substructure. The substructure in turn is often bolstered by a layer of a synthetic fabric.

Many advances in the synthesis and processing of polymers aim to increase their performance under mechanical stress and in various chemical and thermal environments. Polymer scientists are now attempting to produce materials suited to another kind of application, one that exploits the electrical character of the macromolecules. Traditionally polymers have served as insulators or packaging materials in electronics, duties for which the insulating nature of most polymers suits them. More recently they have taken on new roles, notably as photoresists or electron-beam resists: the masking materials on which circuit patterns are imprinted by light, radiation or electron beams during the making of microchips. It now seems that certain polymers, appropriately modified, could play an active, current-



LIQUID-CRYSTALLINE POLYMER known as Vectra, a product of the Celanese Corporation, spontaneously assumed an intricate morphology when it was injected into a mold. After the solidified specimen was broken open a scanning electron micrograph (*left*) revealed two major features: a layered skin consisting of fibers and platelets aligned in a single direction and a core with a less orderly structure. The skin had developed as the molten polymer flowed along the walls of the mold, causing its rodlike molecules (typical of a liquid-crystalline polymer) to become oriented in the direction of flow. The orientation of the molecules is suggested in a scanning electron micrograph showing a fractured surface of the skin (*right*) and revealing a grain much like that of wood. The injection-molded polymer is extremely stiff along the axis of molecular orientation, just as wood is stiff along the grain.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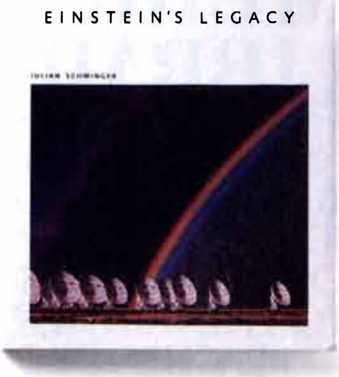

Nobel laureate Julian Schwinger tells the story of one of the twentieth century's greatest achievements—the theory of relativity—which is largely the work of one man: Albert Einstein.

The groundwork was laid in the seventeenth century by Isaac Newton, who unified motion on Earth and in the heavens in a framework of absolute space and time; then, in the nineteenth century by James Clerk Maxwell, who unified electricity, magnetism, and light. But it was left to the sixteen-year-old Einstein to glimpse, for the first time, that the theories of these two giants were incompatible.

Schwinger makes a lively narrative of Einstein's quest for the reconciliation of this conflict, a quest that led to the unification of matter and energy, and of space and time in his special and general theories of relativity.

The special theory has had its awesome confirmation in mankind's command of the nuclear force. Schwinger shows how the general theory, in turn, has stood up for 70 years to experiments drawn from the theory by Einstein, himself, and by his successors, employing ever more ingenious instrumentation and carrying the proofs ever farther beyond the decimal point.

In the last chapter, Schwinger describes space-age experiments made possible by the technologies that incorporate the theory itself. Their outcomes may not only secure further confirmation of Einstein's legacy, but face it with difficulties that lead on towards a still more comprehensive theory.

Julian Schwinger was awarded the Einstein Prize in 1951, the National Medal of Science in 1964, and the Nobel Prize for physics in 1965.

He is currently University Professor of the University of California, Los Angeles. He received his Ph.D. from Columbia University and has been on the faculty at Purdue University and Harvard University. Through the years, he has done theoretical work in various areas of both classical and quantum physics.

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P.W. Atkins

EXTINCTION
Steven M. Stanley (in preparation)

FIRE
John W. Lyons

THE LIVING CELL
Christian de Duve

FOSSILS
George Gaylord Simpson

MATHEMATICS AND OPTIMAL FORM
Stefan Hildebrandt and Anthony J. Tromba

ON SIZE AND LIFE
Thomas A. McMahon and John Tyler Bonner

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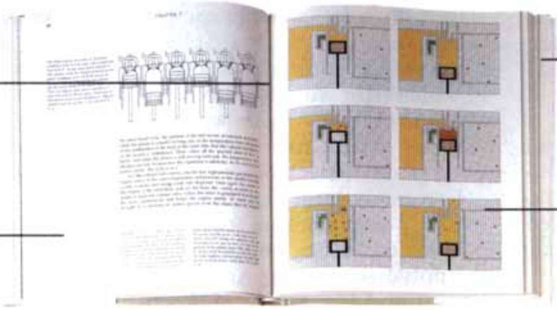

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carrying part in electronic systems.

The electrical conductivity of a material reflects its electronic structure. The electrons surrounding an atom occupy specific orbitals characterized by discrete energy levels. When the orbitals of many atoms overlap in a solid, the electrons become delocalized: no longer associated with a particular atom. At the same time the discrete energy levels broaden into bands of allowable energies, each band able to accommodate a specific number of electrons. If the uppermost occupied energy band in a solid is only partially filled, the material will be conductive; if the band is completely filled, the material will be a semiconductor or an insulator.

In polymers in which pairs of adjacent carbon atoms are linked by double bonds, orbitals overlap along the polymer chain and energy states are transformed into bands. The uppermost occupied energy band is filled. Electrons must be promoted into the vacant energy band above it to make the polymer molecule conductive along its axis.

By doping such a polymer (introducing particular impurities into it) the conductivity can be vastly increased. The dopant is believed to act by removing electrons or adding them to the polymer chains. Either the full energy band loses electrons or the unoccupied band above it gains them; the material thereby acquires the partially filled energy band that is needed for conduction. In one of the earliest conducting polymers to be developed, polyacetylene, doping with arsenic pentafluoride can raise the material's conductivity by 10 orders of magnitude, to the level of some metals.

The theoretical understanding of conductivity in polymers is still not complete, and practical barriers to the routine use of the materials remain. Many of the polymers that can be made conductive have aromatic main chains, because aromatic groups contain double bonds and so are characterized by overlapping orbitals. Such rigid-rod conducting polymers are difficult to process because they are resistant to heat and solvents; they are also quite brittle. In an effort to reduce those drawbacks Mark Druy, Michael Rubner and Sukant Tripathy of GTE Laboratories have blended conducting polymers with elastomers, which can toughen the conducting materials and make them easier to soften and mold.

Certain polymers can be manipulated to display another kind of behavior involving electronic structure. Light is associated with an oscillating electric field, which interacts with the electronic structure in matter. In response to the electric field of very intense light the optical properties of certain materials change. Such nonlinear optical behavior can manifest itself as a change in optical absorption or refractive index. The development of materials with a large nonlinear response could open the way to a fully optical computer or communications system, in which light would control the propagation of other light beams just as streams of electrons control one another in microelectronics.

Extremely large optical nonlinearities have recently been found in a class of semiconducting polymers known as the polydiacetylenes; Anthony F. Garito of the University of Pennsylvania and Alan Buckley of the Celanese Research Company have also found dramatic nonlinearities in certain rigid-rod polymers such as poly(para phenylene benzobisimidazole) (PBI). The behavior is thought to reflect the overlap of orbitals along the polymer axis. When intense light of a particular wavelength strikes the molecule at a specific angle, it excites the delocalized electrons in such a way that their response to a second beam of light is altered. The altered response is evident as a momentary change in the material's refractive index. In a practical device based on the effect the nonlinear material should be free of defects that scatter light. To that end Mrinal Thakur of GTE Laboratories has succeeded in growing single-crystal polydiacetylene films that approach optical perfection.

Versatile as they are proving to be, polymers serve primarily as structural materials, whose mechanical properties are paramount. Given the ability of processing as well as molecular synthesis to improve the mechanical performance of polymers, workers will continue to seek advantageous new ways to arrange macromolecules. For guidance they would do well to look to biology.

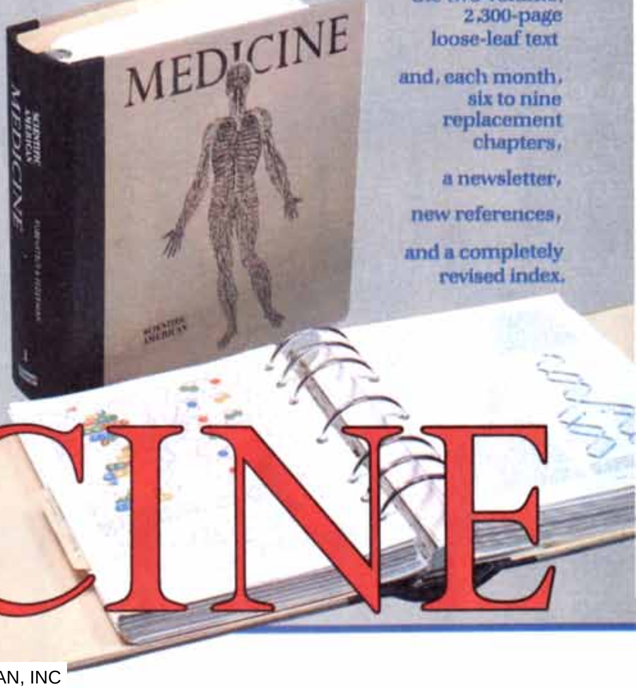
The architecture of tendon is instructive. Tendon is made up mostly of the fibrous protein collagen, a biological polymer, embedded in a gel-like matrix of other substances. Its structure is hierarchical, displaying six different levels of organization. At increasingly fine levels the bulk structure (tendon itself) can be resolved into fascicles, fibrils, subfibrils, microfibrils and finally the macromolecule: tropocollagen, a triple helix of protein chains. The architecture of the structure mirrors the stresses it must undergo: at every level it is oriented along a single axis, and the fibrils have a crimped, or wavy, aspect that adds to their elasticity.

Moreover, the hierarchical nature of the structure imparts toughness. When the tendon is under great stress, small elements of the structure fail independently: individual fibrils break up into subfibrils and microfibrils. The local failure absorbs energy, thereby preventing catastrophic failure of the entire system until it has sustained enormous damage.

The same principle of hierarchical organization specifically matched to stress is apparent in many other biological materials. Under its mucous lining, for example, the wall of the intestine is reinforced by crimped collagen fibers. Two oriented arrays of fibers encircle the intestine on a bias, crossing at an angle of about 60 degrees. Both the crimping of the fibers and their biased arrangement enable the intestine to widen and narrow again elastically. The experimental techniques of materials science have revealed other similarly elegant relations between structure and mechanical properties in the wall of the aorta, the disks that separate vertebrae, and the cartilage of joints.

Polymer science is beginning to imitate the principles of hierarchical organization that are embodied in biological tissues. In many new polymer-matrix composites, reinforcing fibers are arrayed in patterns that anticipate the stresses the material will face. A few synthetic polymers even mimic the ability of biological macromolecules to self-assemble into complex structures. Because molecular orientation in liquid-crystalline polymers responds to flow, they can spontaneously assume a complex morphology. One example, studied by my colleagues and me, developed a mica-like layered skin with a high degree of molecular orientation when it was injection-molded. The molecular orientation stiffened the material, and the mica-like layering toughened the polymer surface by enabling it to absorb damage locally.

It is tempting to suggest that the study of biological materials could lead to new hierarchical designs for synthetic polymers. At the very least biology illustrates the power of designing polymers as systems for a particular use. It is certain that the polymers needed to meet the challenges of the 21st century will be conceived not as monolithic materials but as intricately structured materials systems.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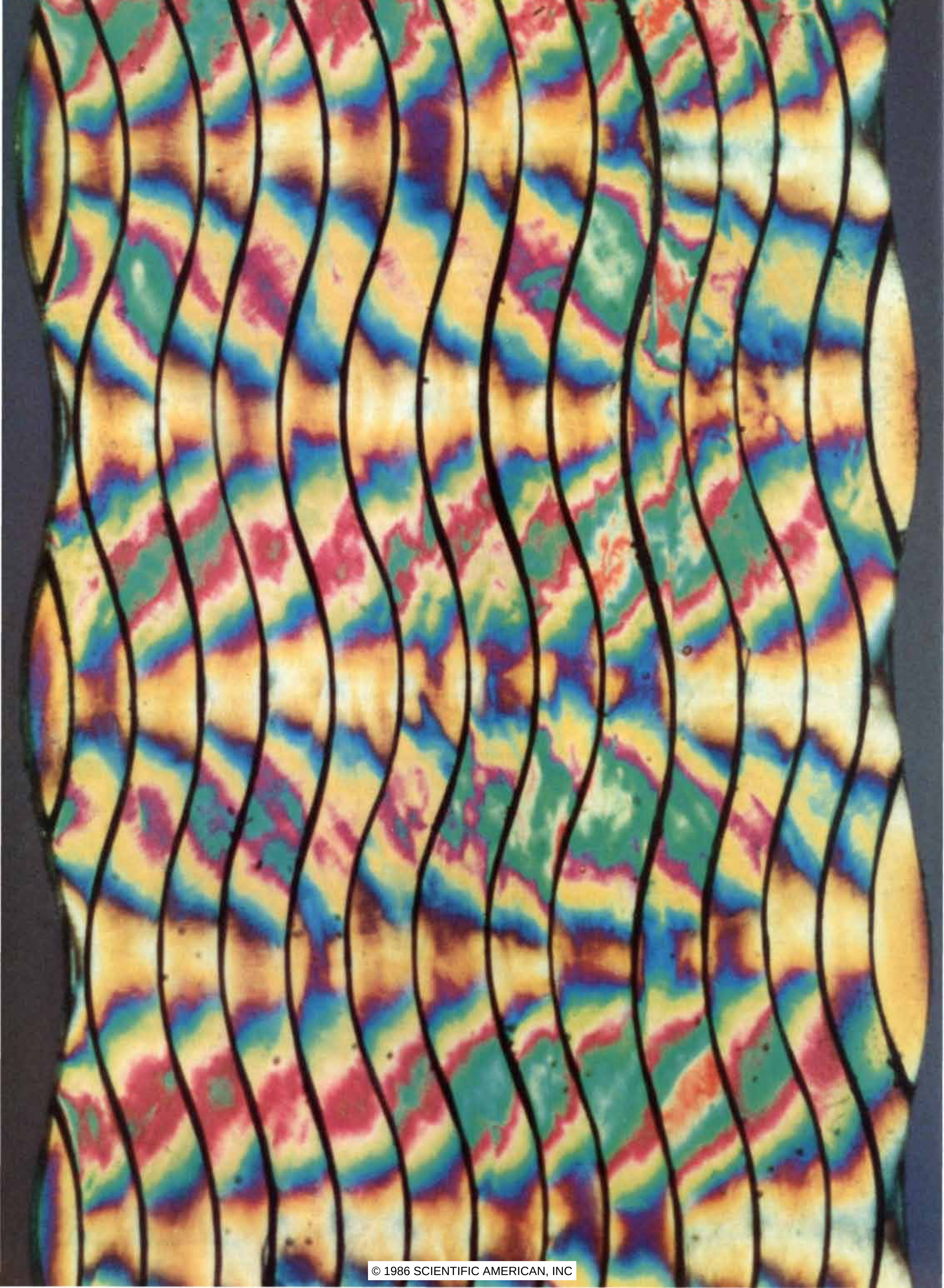


Composites

Composition and internal architecture can be varied freely in these hybrid materials in order to match their performance to the most demanding structural roles

by Tsu-Wei Chou, Roy L. McCullough and R. Byron Pipes

An aircraft that could take off, climb through the atmosphere into space at hypersonic speeds and survive a scorching descent to land at its destination like a conventional airplane might be seen as an ultimate test of structural materials. To power itself into orbit on its own store of fuels the craft would need a structure built of substances at once lightweight and very stiff and strong, able to cope with great aerodynamic stresses. Materials in some parts of the airframe would need to retain their strength at a temperature of more than 1,000 degrees Celsius; materials in the engines would have to remain strong at still higher temperatures. Although such a plane has been proposed, little is certain about its design. There is no doubt, however, about the class of materials from which much of its airframe and some parts of its engines would be made: the hybrid materials known as composites.

The kinds of demand such an aircraft would place on its structure would be extreme but not unprecedented. Already the need for stiffness and strength combined with low density has led designers of military and commercial aircraft, sports equipment and cars to turn to composites for some components. Composites that meet the added requirement of resistance to high temperatures are found in rocket-motor components and missile nose cones. Wherever advancing technology has created a need for combinations of properties no single material can provide, composites are becoming the material of choice. By dispersing fibers or particles of one substance in a matrix, or binder, of another, the designer of a composite can arrive at properties neither material shows on its own.

On the face of it a composite might seem a case of needless complexity. The makings of ideal structural materials would appear to be at hand, in certain elements concentrated in the midsection of the periodic table. Those elements, among them carbon, aluminum, silicon, nitrogen and oxygen, form compounds in which the atoms are joined by strong and stable bonds. As a result such compounds, typified by the ceramics aluminum oxide (the basic stuff of ruby and sapphire), silicon carbide and silicon dioxide (a major component of glass), are strong, stiff and resistant to heat and chemical attack. Their density is low and furthermore their constituent elements are abundant. One of the elements, carbon, displays the same good properties on its own, in the form of graphite.

Yet because of a serious handicap these substances have rarely served as structural materials. They are brittle; a small scratch or internal flaw is enough to initiate a fatal crack. Their susceptibility to cracks means such materials rarely realize their theoretical strength: in bulk form the substance is unlikely to be free of small flaws, or to remain free of them for long in actual use.

When such a material is produced in the form of particles or fine fibers (the commoner case), its useful strength is greatly increased. Whereas window glass is weakened by its tendency to shatter, similar glass spun into fine fibers has a tensile strength of more than half a million pounds per square inch, or three billion pascals. (A pascal is a force of one newton exerted over an area of one square meter.) The tensile strength of ordinary steel, in comparison, is half a billion pascals. The remarkable increase in strength at small scales is in part a statistical phenomenon: the probability that a sample of material will contain a flaw large enough to cause brittle failure goes down as the sample size is reduced. If one fiber in an assemblage does fail, moreover, the crack cannot propagate further and the other fibers remain intact. In a similar amount of the bulk material, in contrast, the initial crack might have led to complete fracture.

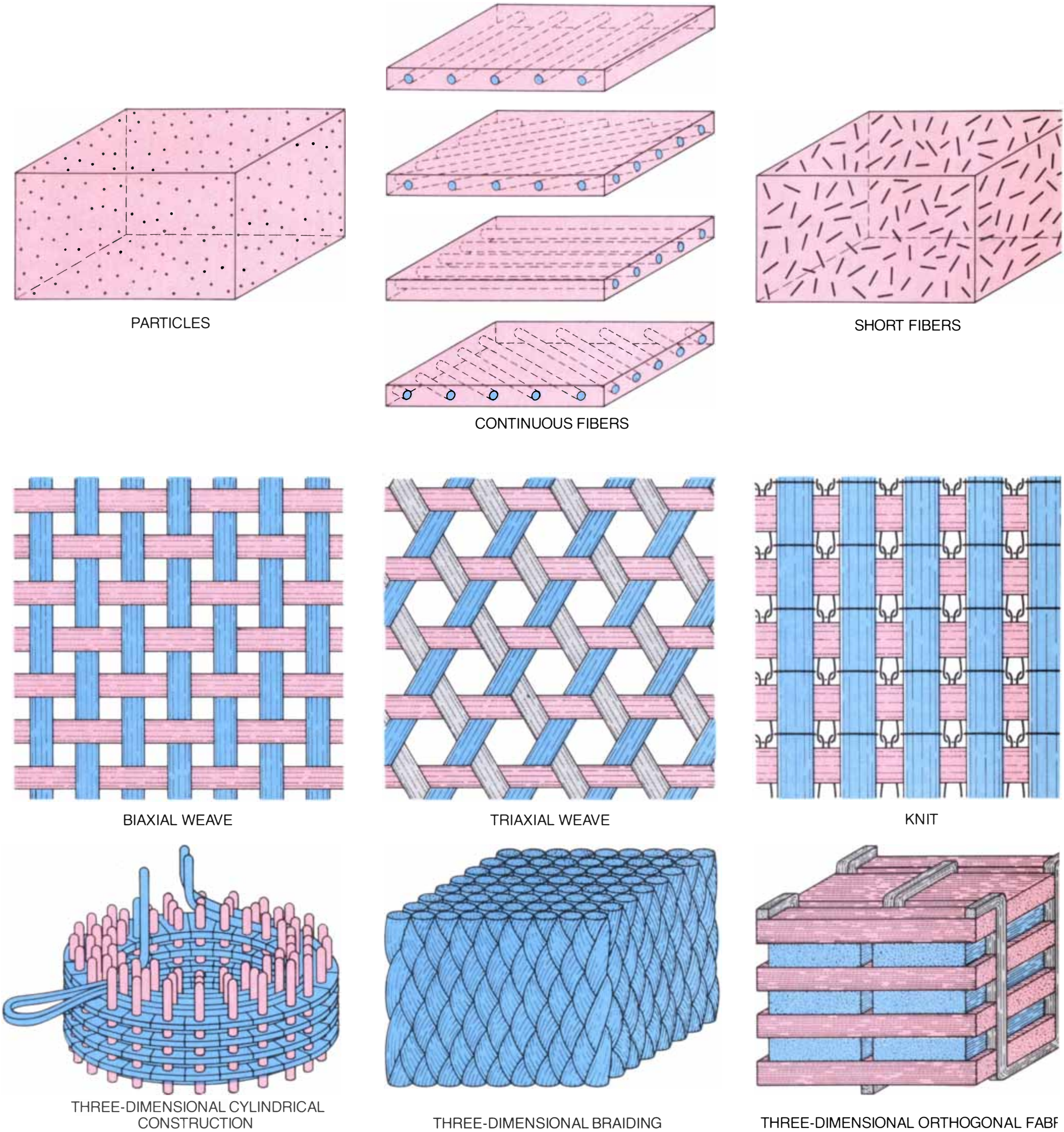
Tiny needlelike structures called whiskers, made of substances such as silicon carbide and aluminum oxide, also contain fewer flaws and show greater strength than the material in bulk form. Whiskers are less likely to contain defects than the bulk material not only for statistical reasons but also because they are produced as single crystals that have a theoretically perfect geometry.

The notion that many materials perform best as fibers also holds for certain organic polymers. Polymer molecules are built as a long chain of atoms, usually carbon, joined by covalent bonds. Under most conditions the chains are either loosely tangled or crystallized in complex patterns. They can be pulled apart fairly

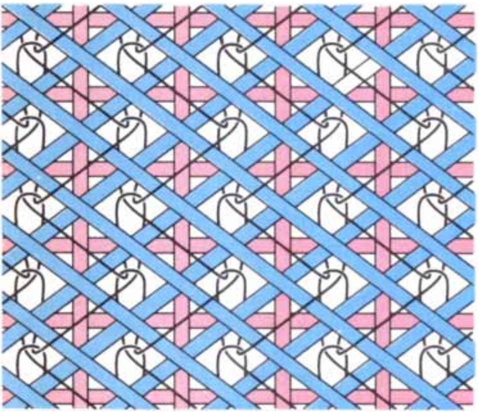
STRESS in a flexible composite made up of undulating graphite fibers embedded in an epoxy matrix is recorded in a tapestry of color. The specimen was placed under tension and photographed through crossed polarizing prisms. Stress changed the optical properties of the matrix, producing colorful interference patterns in the polarized light. As in all composites, the fibers and matrix together display novel mechanical behavior. At low stresses the composite is easily extensible; when the fibers straighten out (deforming the edges of the matrix into a scalloped pattern), it becomes much stiffer. The composite that is shown is not a practical material; instead it is an experimental system for examining the effects of fiber undulation on the properties of composites. One of the authors (Chou) and his colleagues Chen-Ming Kuo, Shen-Yi Luo and Kai-Wen Xianyu made the image.

easily, and the bulk material is flexible and weak as a result. If the chains are all oriented in the direction of stress, however, the polymer can be very strong and stiff. Certain polymer molecules are rodlike, and they readily become aligned when the polymer is spun into a fiber; the production of aramid fibers, which are notable for their strength and stiffness, is based on this effect. Polymers with flexible chains, such as polyethylene, can also be made into extremely strong and stiff fibers through new techniques that extend and orient the polymer molecules along the fiber axis.

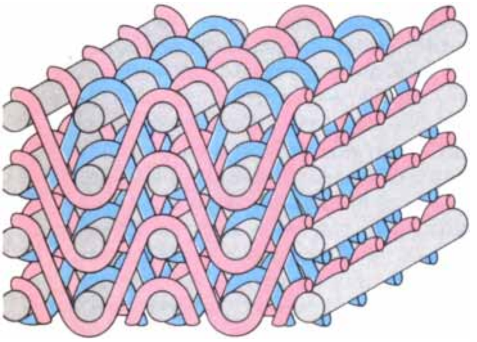
Composites are a strategy for producing advanced materials that take advantage of the enhanced properties of fibers. A bundle of fibers has



REINFORCING GEOMETRIES of composites can be grouped roughly by the shape of the reinforcing elements: particles, continuous fibers or short fibers (*top*). Sets of parallel continuous fibers are often embedded in thin composite layers, which are assembled into a laminate. Alternatively, each ply in a laminate can be reinforced with continuous fibers woven or knitted (*middle*) into a textile “preform,” produced in the width and length of the finished composite structure. Recently developed geometries dispense with lamination: the fibers are woven or braided in three dimensions (*bottom*), a strategy that in some cases enables the final shape of the composite to be formed directly. In choosing among reinforcing patterns composite designers consider cost and mechanical little structural value. To harness their strength in a practical material the designer of a composite embeds them in a matrix of another material. The matrix acts as an adhesive, binding the fibers and lending solidity to the material. It also protects the fibers from environmental stress and physical damage that could initiate cracks.



MULTIAXIAL MULTILAYER WARP KNIT



ANGLE-INTERLOCK CONSTRUCTION

characteristics, for example the directions in which the pattern provides strength. Scott Fowser, Azar P. Majidi and Jenn-Ming Yang of the University of Delaware and Frank Ko of Drexel University provided materials used to make the illustration.

The strength and stiffness of the composite remain very much a function of the reinforcing material, but the matrix makes its own contribution to properties. The ability of the composite material to conduct heat and current, for example, is heavily influenced by the conductivity of the matrix. The mechanical behavior of the composite is also governed not by the fibers alone but by a synergy between the fibers and the matrix.

The ultimate tensile strength of a composite is a product of the synergy. When a bundle of fibers without a surrounding matrix is stressed, the failure of a single fiber eliminates it as a load carrier. The stress it had borne shifts to the remaining intact fibers, moving them closer to failure. If the fibers are embedded in a matrix, on the other hand, fracture does not end the mechanical function of a fiber.

The reason is that matrix materials are usually ductile: elastic or plastic. As the broken ends of the fiber pull apart, elastic deformation or plastic flow of the matrix exerts shear forces, gradually building stress back into the fragments. Because of such load transfer the fiber continues to contribute some reinforcement to the composite. The stress on the surrounding intact fibers increases less than it would in the absence of the matrix, and the composite is able to bear more stress without fracturing. The synergy of the fibers and the matrix can thus strengthen the composite and also toughen it, by increasing the amount of work needed to fracture it.

Although the general requirement that the matrix be ductile provides some guidance for choosing a matrix material, the commonest determinant of the choice is the range of temperatures the composite will face in its intended use. Composites exposed to temperatures of no more than between 100 and 200 degrees C. usually have a matrix of polymer. Most composites belong to this group; "fiberglass," for example, the prototypical composite, consists of short glass fibers embedded in polyester. It is often found in appliances, boats and car bodies because it not only reduces the weight of a component but also lowers production costs by making it possible, for example, to injection-mold a complex structure as a single piece. Most of the advanced composites developed for aircraft surfaces and structural members also consolidate stiff and strong fibers such as graphite or aramid in a polymer, usually one with greater heat resistance than polyester.

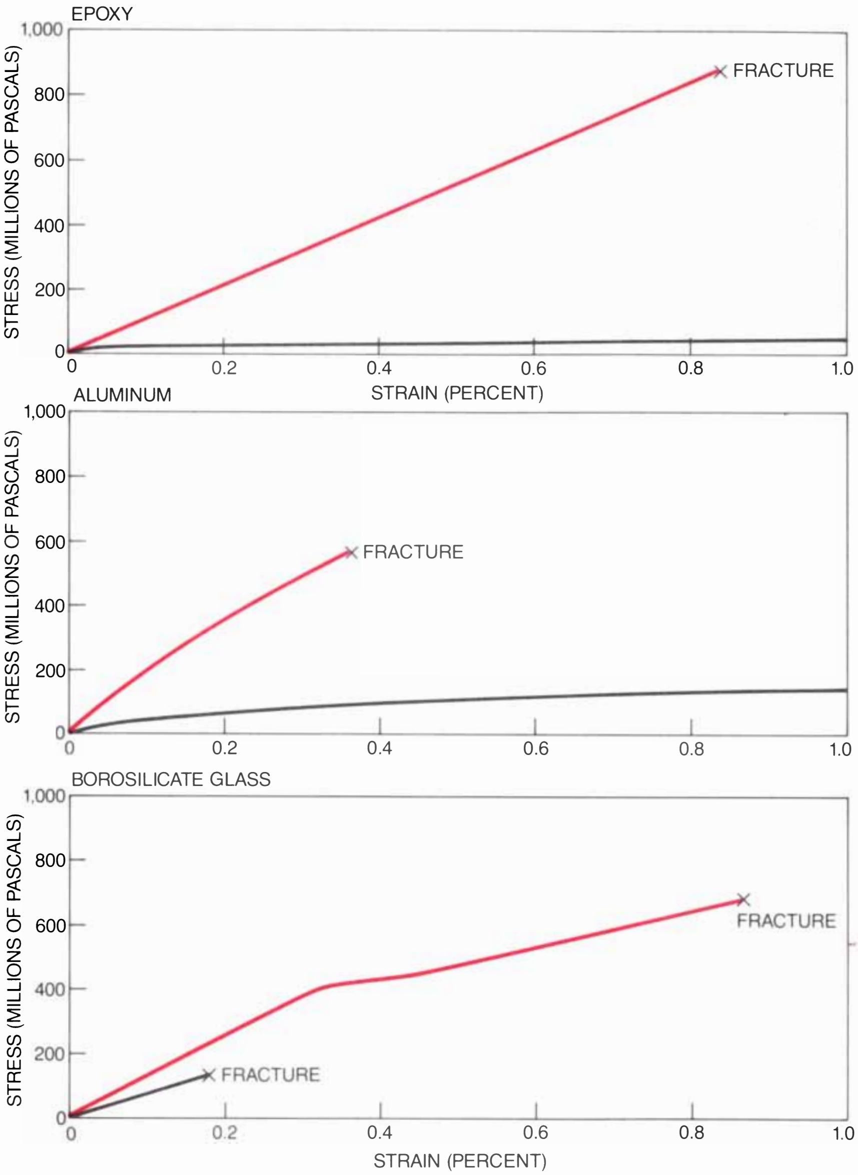
Polymer matrixes are often thermosets, that is, polymers in which bonds between the polymer chains lock the molecular structure into a rigid three-dimensional network that cannot be melted. Thermosets resist heat better than most thermoplastics, the other class of polymeric materials, which melt when they are heated because no bonds cross-link the polymer chains. Epoxies are the commonest thermosetting matrix for high-performance composites, but a class of resins called polyimides, which can survive continuous exposure to temperatures of more than 300 degrees C., are attracting growing interest.

The choice of a matrix determines how the composite must be fabricated. In the making of a typical polymer-matrix composite the fibers, usually in the form of yarns, or bundles, are impregnated with the matrix resin. They can then be formed into tapes or sheets, which are often assembled by hand into a laminated structure; the impregnated fibers can also be directly consolidated into an object by a process called filament winding. If the resin is a thermoset, the structure must then be cured: subjected to conditions that enable the polymer chains to cross-link. Often the composite must be held at high temperature and pressure for many hours.

In part to shorten the processing time, workers are now developing thermoplastic matrix materials; one promising example is a polymer called PEEK (polyetheretherketone). Unifying a composite that has a thermoplastic matrix requires only relatively short exposure to a temperature that is sufficient to soften the plastic. The melting temperature of some thermoplastic matrixes is so high that they rival thermosets in heat resistance; PEEK, for example, melts at 334 degrees C. Thermoplastics have the additional advantage of being tougher than most of the thermosets.

Temperatures high enough to melt or degrade a polymer matrix call for another kind of matrix material, often a metal. Along with temperature resistance a metal matrix offers other benefits. Its higher strength supplements that of the reinforcing fibers, and its ductility lends toughness to the composite. A metal matrix exacts two prices: density that is high in comparison with polymers, even though the light metals aluminum, magnesium and titanium are the commonest matrixes, and complexity of processing. Indeed, whereas the production of many advanced polymer-matrix composites has become routine, the development of metal-matrix composites has progressed more slowly, in part because of the extreme processing conditions needed to surround high-strength fibers with a matrix of metal.

The most obvious strategy, to infiltrate an array of fibers with molten metal, involves very high temperatures. It therefore carries the greatest risk of inducing interfacial reactions: chemical reactions between the fibers and the matrix. If the reactions take place in a thin layer, they can act to bind the fibers and the matrix together, but too thick a layer of reaction products can weaken the bond and also degrade the fibers and the matrix themselves.



INCREASE IN STIFFNESS achieved by lacing a matrix material with stiff fibers is evident when curves showing the relation of stress and strain for an unreinforced polymer, metal and ceramic are compared with curves for the corresponding composites (*color*). Stress is expressed here in pascals: newtons of force exerted over each square meter of material. Strain is the proportion by which the stressed material is elongated. Whereas unreinforced epoxy (a polymer) stretches easily, an epoxy-matrix composite containing 50 percent by volume of silicon carbide fibers is far stiffer: its stress/strain curve is steeper (*top*). In an aluminum matrix the same volume of reinforcement, in this case aluminum oxide fibers, also improves stiffness dramatically (*middle*). (Because the fibers are brittle, the composite fails at a much lower strain than unreinforced aluminum does.) A similar fraction of silicon carbide fibers stiffens a matrix of borosilicate glass only slightly but toughens it considerably, increasing the percentage by which it can be strained without breaking (*bottom*). The fibers do so by restraining the growth of matrix cracks that might otherwise lead to fracture. Karl M. Prewo of the United Technologies Research Center, Ravindranath H. Shetty of Zimmer, Inc., and Chou did research summarized in graphs.

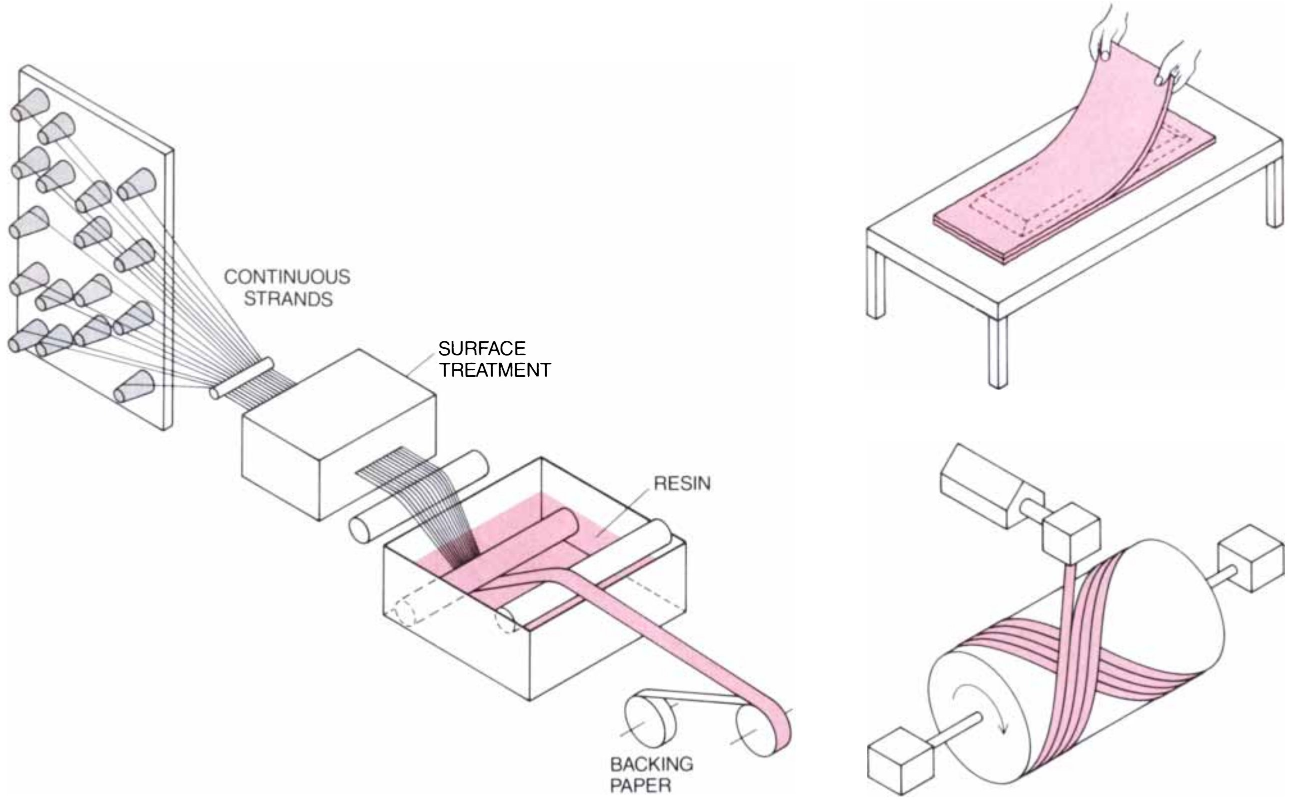
To minimize such reactions fabrication processes requiring lower temperatures have been devised. In one technique, diffusion bonding, matrix metal in the form of foils or a powder is consolidated with fibers at high pressure but at a temperature below the metal's melting point. Solid-state diffusion of the metal atoms unifies the composite. Even at the lower temperatures of diffusion bonding extensive interfacial reactions can take place between a matrix of aluminum or magnesium and fibers of graphite or boron. Such fibers are often coated beforehand with a chemical barrier that limits reactions with the matrix.

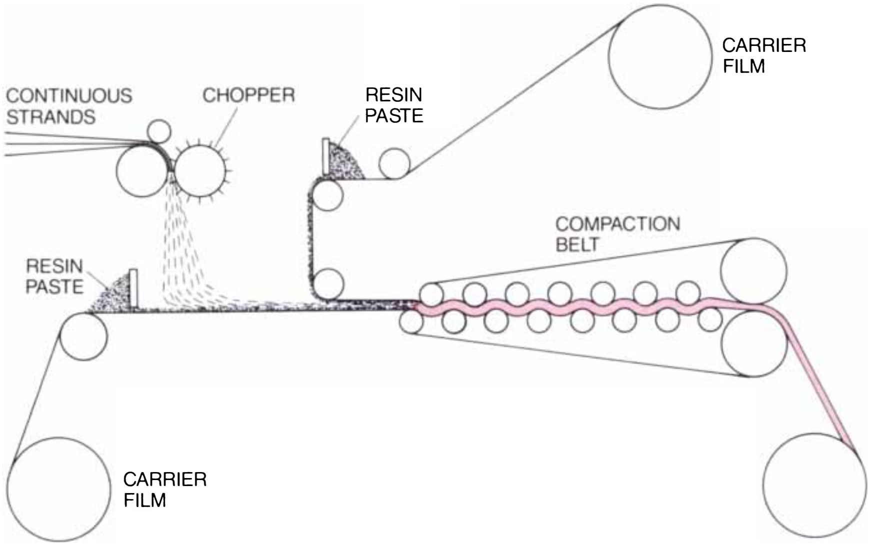
Metal-matrix composites might assume a place in the cooler parts of the skin of a hypersonic aircraft, but at the nose, on leading edges of the wings and in the engines temperatures could exceed the melting point of a metal matrix. For those environments designers are examining a class of composites that have matrixes as resistant to heat as the fibers themselves, and also as lightweight and potentially as strong and stiff: ceramics. Because they are brittle, ceramics behave differently from other matrixes. In metal- and polymer-matrix composites the fibers supply most of the strength, and the ductile matrix acts to toughen the system. A ceramic matrix, in contrast, is already abundantly stiff and strong, but to realize its full potential it needs toughening.

The fibers in a ceramic-matrix composite fill that need by blocking the growth of cracks. A growing crack that encounters a fiber may be deflected or may pull the fiber from the matrix. Both processes absorb energy, slowing the growth of the crack. Even if the matrix becomes riddled with cracks, it will fracture less readily than an unreinforced ceramic because of the many fibers bridging the cracks.

The ceramic matrix gives such composites great temperature resistance. Borosilicate glass reinforced with silicon carbide fibers retains its strength at 1,000 degrees C. Such matrixes as silicon carbide, silicon nitride, aluminum oxide or mullite (a complex compound of aluminum, silicon and oxygen) yield composites that remain serviceable at even higher temperatures, in some cases as high as 1,700 degrees. Many ceramic-matrix composites actually grow tougher, and as a result stronger, as the temperature rises. Between the crystalline grains that make up many ceramics are glassy regions, which soften at high temperatures and act as crack arresters.

The heat resistance of a ceramic-





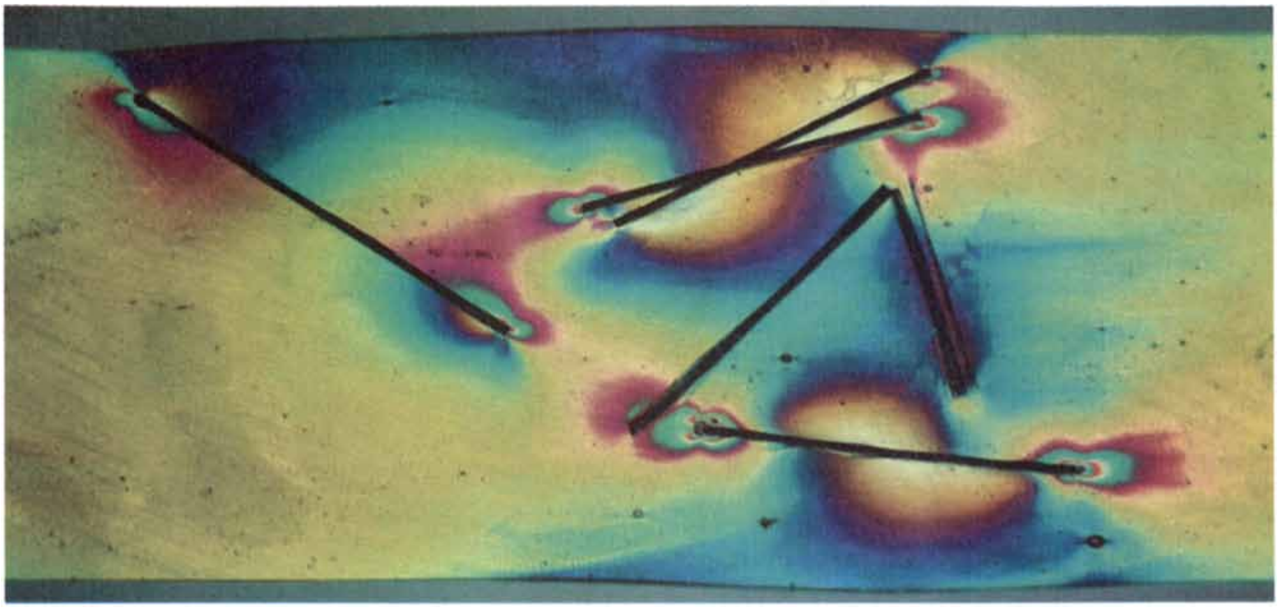
MANUFACTURE of a polymer-matrix composite begins with continuous strands of reinforcing material. In the production of an advanced composite (*above*) the fibers are unwound from bobbins, aligned and, after a surface treatment designed to promote their adhesion to the matrix, coated with the polymeric resin. They are consolidated into tape or sheet that can then be assembled into a laminated structure (*top right*). Alternatively, the impregnated fibers can be wound into a complex shape in a process called filament winding (*middle right*). Usually the finished composite structure must then be cured to harden the matrix. Commercial reinforced plastics strengthened with short fibers are often produced as sheet molding compound (*bottom right*). The strengthening fibers are chopped, dropped into a paste of the matrix material and topped with another layer of paste. The sheet is then consolidated between rollers. The composite is still viscous and can later be molded and cured.

matrix composite complicates its fabrication. For all practical purposes many ceramics cannot be melted, and so unreinforced ceramics are usually shaped by consolidating a ceramic powder at high temperature and pressure in a process known as sintering. One means of producing a ceramic-matrix composite simply extends that method: short fibers or whiskers are mixed with the ceramic powder before it is sintered. If the reinforcement takes the form of long fibers or yarns, it can be impregnated with a slurry of ceramic particles dispersed in a liquid; the yarns are then sintered together. Matrixes of glass lend themselves to more conventional fabrication techniques, because they can be softened. Reinforcing yarns can be imbued with very hot, viscous glass and pressed together to form the finished composite structure.

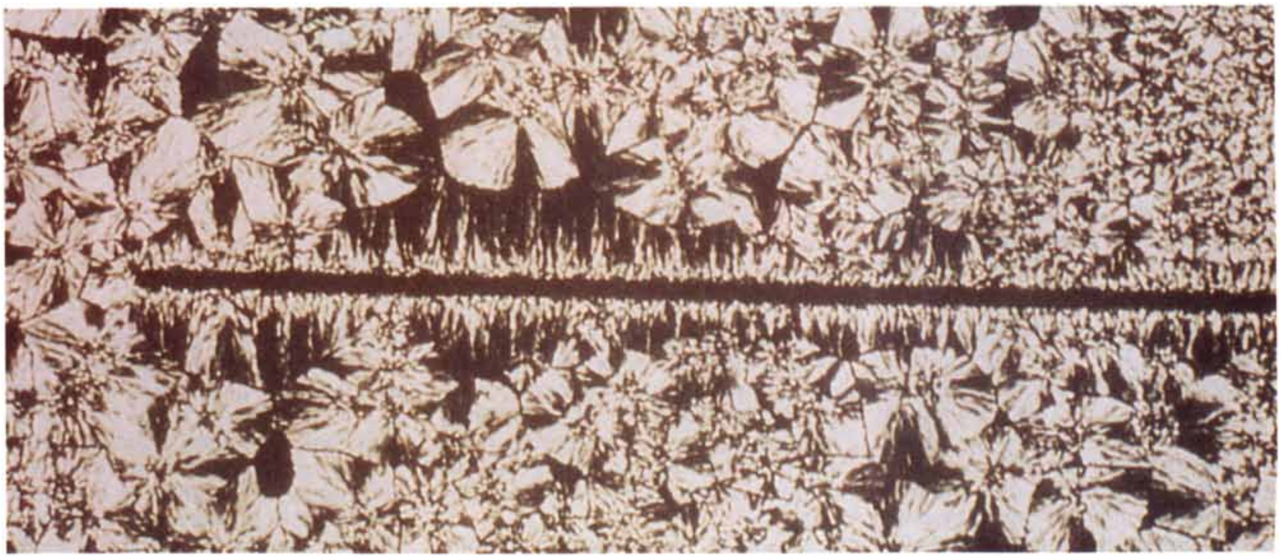
Related to ceramic-matrix composites in character but distinctive in manufacture is a composite in which both the matrix and the reinforcing fibers consist of elemental carbon. Carbon-carbon composite is reinforced by the element in a semicrystalline form, graphite; in the matrix the carbon is usually amorphous. Carbon-carbon composite retains much of its strength at 2,500 degrees C. and is used in the nose cones of reentry vehicles. Unlike most ceramic-matrix composites, it is vulnerable to oxidation at high temperatures. A thin layer of ceramic is often applied to the surface of a carbon-carbon composite to protect it.

The first steps in the production of carbon-carbon composite resemble the making of a polymer-matrix material. Graphite fibers are impregnated with a phenolic resin, a kind of polymer. The resin-soaked assemblage is then heated in an inert atmosphere, pyrolyzing the resin—charring it, like wood being converted into charcoal—to leave a carbon residue. The composite is reimpregnated with resin under high pressure and pyrolyzed again; many repetitions of the process yield a sound structure with a minimum of voids. Another way to build up the matrix is chemical-vapor deposition, in which the breakdown of an organic gas deposits carbon among the fibers.

The temperatures at which a composite will be employed largely dictate the matrix choice. How are the reinforcing fibers selected? All the ceramic, polymer and elemental reinforcements are strong, but they differ in other respects. The tensile strength of glass fibers, for example, equals or surpasses that of graphite fibers, a mainstay of many high-performance composites. Glass fibers stretch by



INTERACTION OF FIBERS AND MATRIX is illustrated by an image of a sample composite that was held under tension and photographed through crossed polarizers. The epoxy matrix is reinforced with short, rigid bundles of graphite fibers. Stress in the deformed matrix is revealed by zones of contrasting colors. The fibers restrict the deformation of the adjacent matrix material, causing stress to become concentrated near fiber ends; in short-fiber composites cracks in the matrix often begin there. The colors suggest the complex interplay taking place among the stress fields surrounding neighboring fibers, a phenomenon that greatly complicates the mathematical prediction of the properties of short-fiber composites. The photograph was made by Xianyu and Kuo.



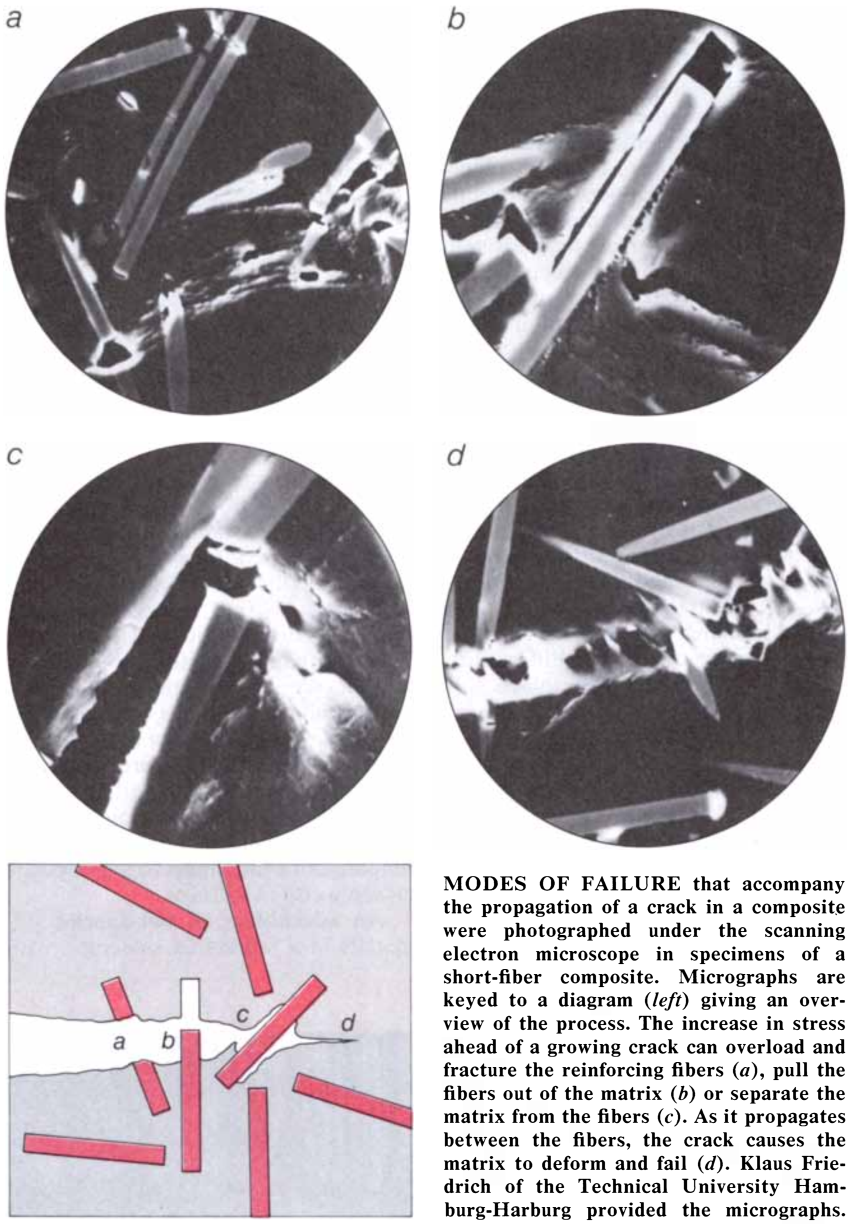
ANOMALOUS STRUCTURES developed around a fiber embedded in a polymer matrix. In many composites unusual physical and chemical processes at fiber surfaces affect local properties of the matrix; the photograph illustrates one such event. As this thermoplastic polymer cooled from the melt, crystal growth distant from the fiber radiated from nucleation points to form sunburstlike "spherulites," a morphology typical of many polymers. Nucleation around the fiber, in contrast, created a sheath of needlelike crystallites. Such semicrystalline polymers can themselves be regarded as composites, made up of a variety of reinforcing crystal structures within a matrix of less-ordered regions. The micrograph was provided by Imperial Chemicals Industries, Ltd.

several percent of their length when they are under great stress, however. Hence glass-reinforced composites are not suited to high-performance applications in which stiffness is crucial. Their low cost has nonetheless made them widespread in less demanding applications.

Certain reinforcements may be better suited than graphite is to roles in which the composite must show high impact resistance. The airframe of a combat helicopter must stay intact when it is hit by gunfire, and so the reinforcement in its composite skin might be the tougher, if somewhat less stiff, polymeric fibers of aramid. Fibers made of the element boron, in contrast, are even stiffer than graphite fibers. They were once a standard high-performance reinforcement but have fallen out of favor in part because they are costly and, compared with graphite, dense.

Reinforcing fibers must be not only mechanically but also chemically suited to their role. Clearly they must be able to withstand the processing conditions demanded by the matrix. Aramid fibers would char if they were exposed to the heat needed to consolidate a metal-matrix composite, and graphite fibers incorporated into a metal or ceramic matrix oxidize and become weakened unless the high-temperature processing is carried out in an inert atmosphere.

Chemical compatibility between the fibers and the matrix is most crucial at their point of contact: the surface of the fibers. In polymer- and metal-matrix composites a bond must develop between the reinforcement and the matrix if they are to act in concert. A prerequisite for adhesion is that the matrix, in its fluid form, be capable of wetting the fibers. Aluminum oxide and silicon carbide are readily wetted by molten metals, and so they often serve as reinforcing fibers in metal-matrix composites. Fibers that would otherwise not be wetted by their matrix can be given a coating that fosters contact by interacting with both the fibers and the matrix. In some cases varying the matrix composition can also promote the process. Once the matrix has wetted the fibers thoroughly, intermolecular forces or chemical reactions can establish a bond.



MODES OF FAILURE that accompany the propagation of a crack in a composite were photographed under the scanning electron microscope in specimens of a short-fiber composite. Micrographs are keyed to a diagram (*left*) giving an overview of the process. The increase in stress ahead of a growing crack can overload and fracture the reinforcing fibers (*a*), pull the fibers out of the matrix (*b*) or separate the matrix from the fibers (*c*). As it propagates between the fibers, the crack causes the matrix to deform and fail (*d*). Klaus Friedrich of the Technical University Hamburg-Harburg provided the micrographs.

The properties of an advanced composite are shaped not only by the kind of matrix and reinforcing materials it contains but also by a factor that is distinct from composition: the geometry of the reinforcement. In some composites the geometry is random. Dispersion-strengthened metals (metals hardened by tiny particles of an impurity, which may be a precipitate that formed as the molten metal cooled or ceramic particles actively dispersed through the metal) are a kind of composite in which only the concentration of the strengthening particles is controlled, not their exact dimensions or orientation. The same holds for many composites containing short fibers, a category that includes many commercial glass-reinforced plastics and some metal- and ceramic-matrix composites reinforced with whiskers.

For two reasons most high-performance composites are strengthened with much longer fibers, usually bundled into continuous yarns. If a composite is to benefit fully from the great strength of the reinforcing material, the reinforcement must be capable of accepting loads that stress it to its breaking point. Otherwise the composite will fail at a load that falls short of the stress the fibers could theoretically sustain; they will simply pull out of the matrix without breaking as the composite disintegrates.

Since load is transferred from the matrix to the reinforcing fibers by means of shear forces acting on their surface, their surface area must be large in relation to their cross-sectional area. In other words, an efficient reinforcing element will be much longer in one dimension than it is in the other two. For most reinforcements the critical aspect ratio, or the ratio of length to diameter at which the fiber becomes capable of sustaining enough stress to break it, is about 100 : 1. The exact figure depends on the strength of the fiber, the character of the matrix and the degree of bonding between them.

Long fibers therefore reinforce a composite more efficiently than short fibers or particles do. There is a second reason continuous fibers have become the dominant form of reinforcement in advanced composites: their orientation can be controlled precisely. The internal structure of the composite can thereby be designed to anticipate the stresses it will face in use.

The internal geometry of conventional high-performance composites resembles that of plywood: they are built up of thin layers, each layer reinforced by continuous fibers running in a single direction. The usual means of making advanced polymer-matrix composites, the preimpregnation of tapes or sheets and their assembly by hand, lends itself to the production of such laminated structures. Successive layers can be oriented in different directions to give the assemblage stiffness and strength along several axes, but such composites are handicapped by the fact that no reinforcing fibers run from layer to layer or transversely within the layers. Under extreme stress the composite can delaminate, its layers peeling apart, and the parallel fibers in the individual plies can separate.

Such unidirectional laminates also lack impact resistance. In metal-matrix composites, for example, the matrix on its own may be quite ductile and therefore tough. The introduction of a dense array of fibers to which the metal is strongly bonded can embrittle it, however, by limiting its ability to dissipate the energy of an impact through plastic deformation. It cracks instead, and in a conventional laminated composite the crack can easily find a path between the layers of fibers. As a result an impact that would only have dented an unreinforced metal might produce extensive damage in a composite in which the same metal serves as the matrix.

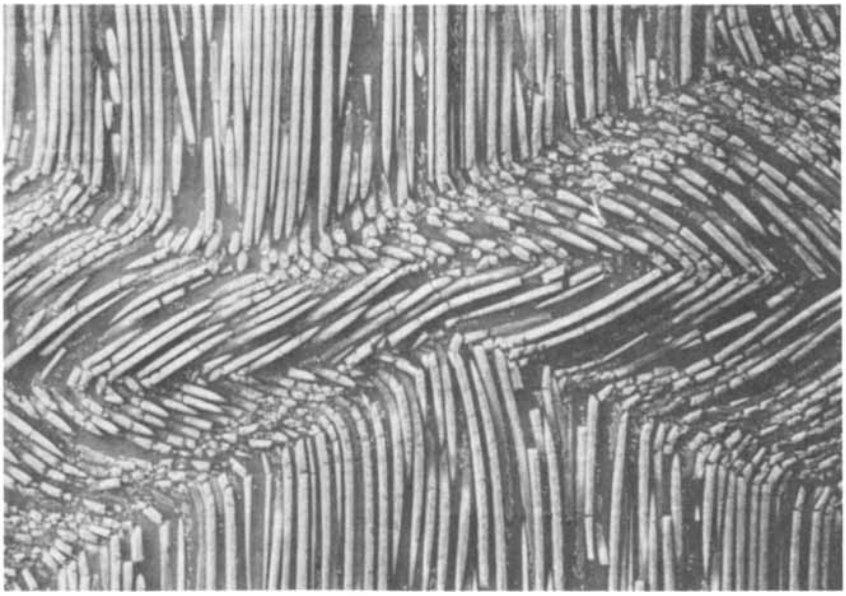
In order to strengthen composites in many directions at once and increase their resistance to impact, composite designers have recently begun deploying the reinforcing fibers in a variety of woven, knitted or braided fabrics. Considerations of cost, directional strength and flexibility govern the choice of a pattern. A simple weave will strengthen a composite the most along the fabric's warp and woof; complex fabrics are more expensive to produce but offer strength in a number of intermediate directions. Certain knits yield an elastic fabric, which can impart extra toughness to a composite at some cost in stiffness.

An assemblage of flat fabrics still results in a laminated structure, with its attendant weaknesses. To eliminate planes of weakness from the composite altogether the reinforcement can be given a three-dimensional geometry. The graphite fibers in carbon-carbon composite, for example, are usually arranged in a three-dimensional orthogonal weave, a pattern in which bundles of yarn are oriented along three mutually perpendicular axes. A composite reinforced with a three-dimensional orthogonal weave is often machined into its final form, but a newly developed technique for braiding long fibers into three-dimensional shapes makes it possible to form complex components directly. Thus the technique not only improves composite performance but also eliminates final fabrication steps, partly offsetting the expense and complexity of making the braided reinforcement and of imbuing the dense fabric with resin or molten metal.

Recent studies have shown that in metal-matrix composites three-dimensional braiding yields a considerable increase in toughness. The research compared the impact resistance of unreinforced aluminum, aluminum reinforced with unidirectional aluminum oxide fibers and aluminum reinforced with bundles of the fibers braided in a three-dimensional pattern. The ductile unreinforced aluminum absorbed considerable impact energy without fracturing, whereas the laminated composite shattered under a much lighter impact. The braided composite, however, could absorb almost as energetic an impact as the unreinforced metal. The "through the thickness" reinforcement provided by the three-dimensional fiber network prevented delamination and forced cracks to follow tortuous paths, thereby increasing the dissipation of impact energy.

The ability to specify not only composition but also internal geometry gives the designer of a composite unmatched control over the material. Exerting that control intelligently, however, requires a body of theory: an ability to predict the effect of each variable on the performance of the product. It is possible to predict the behavior of a laminated composite from prior knowledge of the properties of a single layer. As the possible combinations of fibers and matrix have multiplied and simple laminates have begun giving way to complex fabrics, investigators have sought ways to bypass empiricism. The object is to predict behavior directly, given the characteristics of the fibers and matrix and their configuration.

Many of the properties that influ-



COMPRESSIVE FAILURE of a composite made up of aluminum oxide fibers in a matrix of aluminum took place as the fibers buckled. When such dense fiber arrays kink, adjacent fibers tend to fail and fold in the same direction. As they slide past one another the matrix between the fibers is subjected to shearing. The resistance of the matrix to shearing largely determines compressive strength along the fiber axis, since fibers tend to buckle under longitudinal compression. Shetty and Chou made the photomicrograph.

ence how a composite can be used are determined by the averaged behaviors of the fibers and the matrix. Such properties include stiffness, thermal conductivity, thermal coefficient of expansion and Poisson's ratio (the degree to which a material contracts laterally when it is stretched). Known as thermoelastic properties, they govern the deformation of the material. They determine, for instance, how much a composite spar in an airplane wing will flex under normal loads and how much its shape will change as it is heated and cooled.

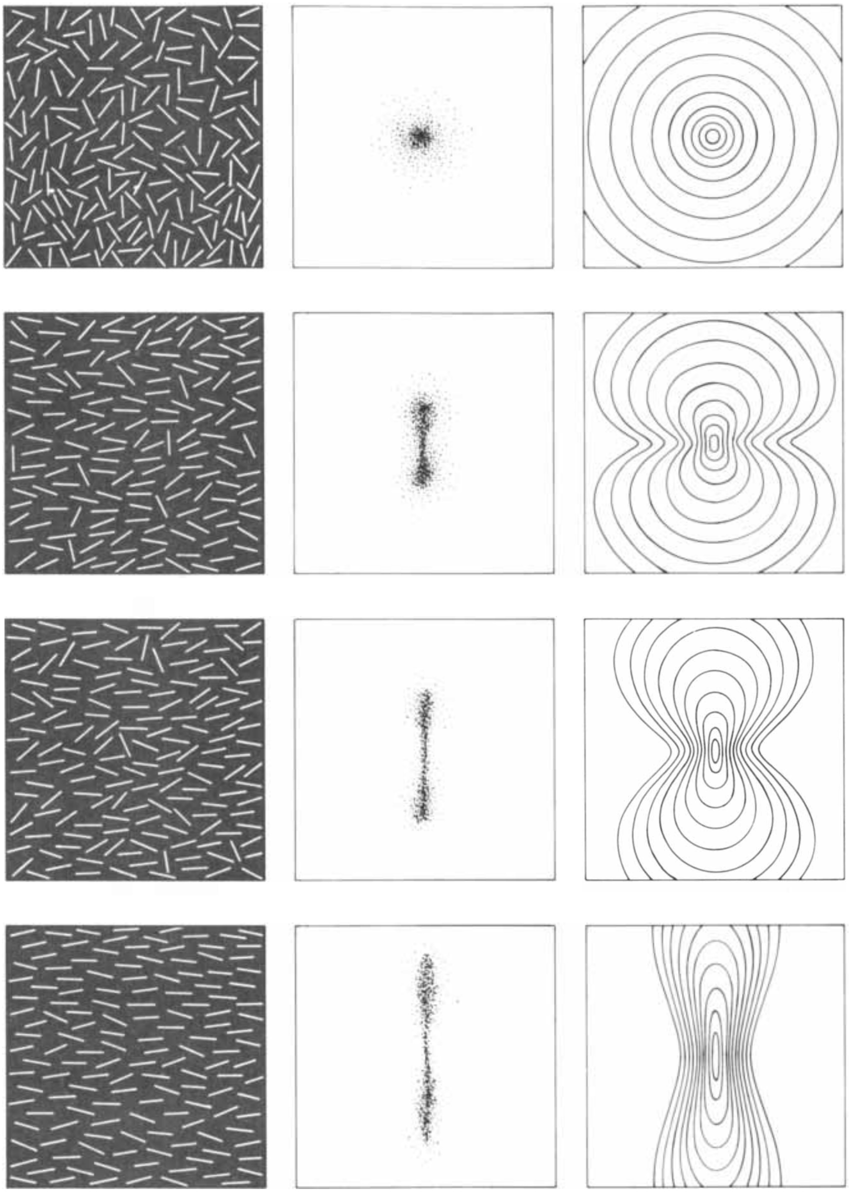
How are such "averaged" properties shaped by the internal geometry of the composite? The influence of fiber orientation on the overall stiffness of a unidirectional composite layer provides an example. Along the axis of the fibers their average stiffness and the average stiffness of the matrix can be seen as acting in parallel. As in a set of stiffer and softer springs working side by side, the stiffer elements dominate the overall response of the system. If the fibers are the stiffer component, as is usually the case, the longitudinal stiffness of the composite will be at least as great as the stiffness of the fibers, multiplied by the fraction of the composite they constitute.

The stiffness of the composite in the transverse direction (across the fibers) can be represented by a number of stiffer and softer springs connected in series, or end to end. That arrangement makes the less stiff springs dominant. Even if the stiffer springs (representing the fibers) are for all practical purposes rigid, the contribution of the softer springs (the matrix) will dominate the overall stiffness of the system.

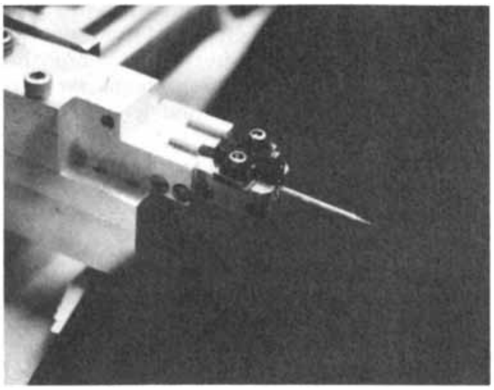
Mathematical analysis incorporating such simplified considerations yields predictions of averaged properties that agree quite well with the observed longitudinal behavior of unidirectional composite layers. Large discrepancies arise in the prediction of properties in other directions; the simple model tends to underpredict the transverse stiffness of a composite, for example. Factors such as the shape of the fibers in cross section and their packing arrangement influence properties across the fibers.

Over the past two decades many workers have refined techniques for predicting thermoelastic properties in advanced composites. Predictive models for unidirectional layers have advanced the furthest and now can adequately describe thermoelastic properties over the length, width and thickness of a composite built of such layers. Rigorous models that can predict the behavior of composites reinforced with flat fabrics and three-dimensional weaves are also under development.

Investigators have had to resort to more approximate treatments in predicting the properties of short-fiber composites such as glass-reinforced polyester. Their internal geometry is less well defined than that of continuous-fiber composites: the orientation of their reinforcing fibers is imperfect, when it is not random, and in any sample of material the fiber length varies. Successful prediction of thermoelastic properties in short-fiber composites requires information on the range of fiber orientations and lengths. Small



FIBER ORIENTATION in a short-fiber composite can be determined quantitatively by a technique, devised at the University of Delaware, in which a micrograph of the composite serves as a diffraction grating. When light is passed through a photographic negative of the image, the short reinforcing fibers, which appear white against a dark background (*left*), act as the slits in the grating. Light passing through each slit spreads at right angles to the slit axis; consequently the diffraction pattern has its longest dimension perpendicular to the direction of fiber orientation. Matching the recorded diffraction pattern (*center*) with a theoretical pattern calculated for a specific degree of fiber orientation (*right*) yields a measure of the actual fiber orientation. As the orientation increases (*top to bottom*), the properties of the composite become more directional. Tensile strength and stiffness in a short-fiber composite, for example, are greatest along the orientation axis.



variations in processing can strongly influence those distributions, for example by resulting in extensive filament breakage or creating flow patterns in the resin that align the fibers in one or several directions. Hence complete theoretical descriptions of the performance of short-fiber composites will need to predict first the effects of processing on internal structure and, in turn, the effects of internal structure on properties.

It is far less straightforward to predict a composite's ultimate performance under tensile, compressive and shear loads than it is to predict thermoelastic properties such as stiffness. Strength is determined not by the average performance of each component in a composite but by localized defects. They act as weak links, limiting the ultimate strength of the composite no matter how strong the rest of the material is. Common defects such as local delamination exert less influence on composite performance than they once did, owing to improved fabrication methods and such techniques for detecting flaws as scanning the finished composite with ultrasound. But reinforcing fibers themselves vary in strength, and the precise location and strength of the weakest fiber element cannot be anticipated.

The strength of a composite must therefore be described in terms of the statistical variation in fiber strengths. In making such a prediction one must also take into account factors influencing the likelihood that the fracture of a weak fiber will spread to other fibers and lead to the failure of the composite as a whole. One factor is the efficiency with which load is transferred between the matrix and the fibers. If the pieces of the broken fiber continue to be stressed by the matrix, less load will be transferred to adjacent, intact fibers and so their chances of also failing will be reduced.

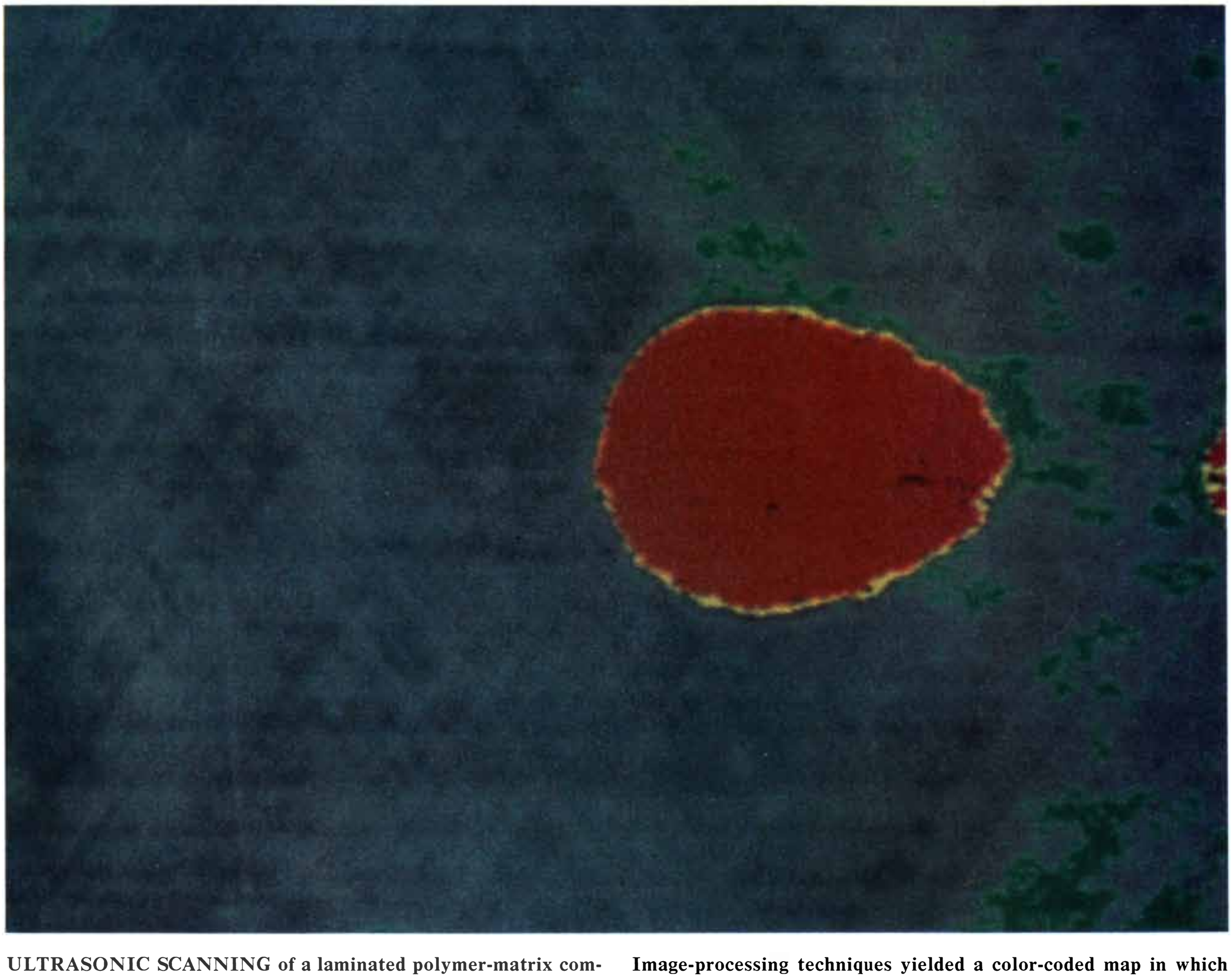
Another factor bearing on fracture growth, and hence ultimate strength, is the brittleness of the matrix. As a fiber breaks it releases a pulse of energy; in a brittle matrix the energy may start a crack that can propagate across the matrix to an adjacent fiber. Unless the bond between the matrix and the second fiber is quite weak the crack may cause it to fail as well. Consequently the adhesion of the matrix to the fibers also has an influence on the ultimate strength of a composite. In a brittle matrix, such as a ceramic, a fairly weak bond toughens the composite and thereby increases its practical strength, even though a strong bond ordinarily enables fibers to reinforce a composite most efficiently.

Progress toward a theoretical basis for managing the many variables of composite design has encouraged investigators to contemplate new complexities. An ordinary composite reinforced with stiff, straight fibers usually displays a nearly constant value of stiffness: tensile strain, or the degree of elongation, increases in a linear relation to the tensile stress applied to the composite. New composites designed to display specific nonlinear relations of strain and stress are now attracting interest.

One such material, a composite consisting of undulating fibers in an elastomeric, or rubbery, matrix, can elongate readily at low stresses but stiffens when the fibers become fully extended. A hybrid composite strengthened with two kinds of fibers, some of them brittle and inextensible and the others ductile and tough, can display the opposite behavior. The stiff fibers cause stress to increase very sharply at low strains, but when the strain is sufficient to break the stiff, brittle fibers, the curve of stress over strain flattens. The ductile fibers come into play and as a result the composite becomes more extensible. The hybrid design can yield a material that combines much of the stiffness of an ordinary composite containing only stiff fibers with increased toughness.

The degree of control over material properties that is typified by hybrid composites is transforming engineering design. In part because homogeneous materials such as metals and alloys do not offer comparable control, specifying a material and designing a component have traditionally taken place separately. As composites begin to replace traditional materials in fields such as aerospace, component design and the specification of a material are merging and becoming aspects of a single process.

The controllable microstructure of a composite allows it to be tailored to match the distribution of stresses to which it will be subject. At the same time components must come to reflect the distinctive nature of composites: their directional properties and the intricate forms they can be given through processes such as injection molding, filament winding and three-dimensional weaving. The complexity inherent in conceiving components and their materials at the same time suggests engineering design will grow increasingly dependent on computers and multidisciplinary teams. Such an approach will harness the full potential of composites for the technologies of the future.



ULTRASONIC SCANNING of a laminated polymer-matrix composite reveals flaws that can rob the material of strength. Ultrasonic waves were reflected from the internal structure of the composite. Computerized analysis of the reflected energy took into account features such as refraction (bending), travel time and attenuation to locate flaws and distinguish among the various kinds. Image-processing techniques yielded a color-coded map in which red corresponds to a delamination, green signifies regions that are porous or overly rich in matrix resin and yellow marks flaw boundaries. The fibers that reinforce the composite are shown in gray. Image is reproduced courtesy of Robert A. Blake, Jr., of the Center for Composite Materials at the University of Delaware.

THE AMATEUR SCIENTIST

Cracks in a surface look intricately random but actually develop rather systematically

by Jearl Walker

Sooner or later the surface of almost anything will develop cracks. Often they grow into an intricate network. Although the network may appear to form randomly, in many cases it actually develops systematically according to certain rules. Applying those rules as you look at the places where cracks intersect, you can ascertain how the network formed.

It is instructive to investigate two types of crack network. One of them is the network that develops in drying mud or paint. Similar networks are found in broken pavement, tile, plaster and other materials. Do the cracks tend to intersect at any particular angle? Do the "islands" left by the cracks tend to have any particular geometric shape? Why do the tops of the islands in drying mud sometimes separate and then curl? Are the giant crack networks found on some playas (desert basins that temporarily become shallow lakes after heavy rain) similar to mud cracks?

The other type of crack network is found in some ancient lava flows that formed pools on the surface, cooled, solidified and then cracked so as to form tall columns whose cross sections are hexagons and other polygons. When I walked over an outcropping of such columns at Giant's Causeway in Northern Ireland recently, I was surprised at the regularity of the formation. Why did cooling basalt crack in such an organized way? No one has advanced a definitive answer, but recent theories may have resolved part of the mystery.

When a solid is placed under tensile stress by stretching forces, its molecular bonds resist the elongation. The ratio of the elongation to the initial length is called strain. If the strain is less than 1 percent, the bonds can be regarded as tiny springs linking the molecules; if the stress is removed, the solid regains its initial length as the springs contract. Under a larger strain a ductile solid first is distorted and then breaks. A brittle solid breaks immediately with no distortion.

The mechanism of breaking is by means of cracks that form and then extend through the solid. Imagine a solid block under a uniform vertical stress. Each vertical molecular bond along any horizontal line through the block shares equally in resisting the stress. The stress is said to be uniformly distributed over such a line.

Suppose a small crack appears on one side of the block because of a local weakness in the material or a scratch on the surface. The stress on the block acts to pull apart the two faces of the crack. Molecular bonds are broken; the stress they would have resisted is shifted to the bonds at the tip of the crack, increasing the stress there. It may break those bonds, extending the crack into the block.

The process can be repeated at the new tip. In this way the crack travels though the block. It may move almost as fast as the speed of sound or it may travel in spurts. Its movement tends to be straight unless it encounters points of weakness, in which case the path becomes sinuous.

Suppose the block is under both vertical and horizontal stress when a crack develops horizontally. The vertical stress in the material along the faces of the crack is relieved, but the horizontal stress is still there. It may initiate a side crack that begins to travel at right angles to the original crack. Where points opposite each other on the faces of the original crack are weak, side cracks can develop. They travel in opposite directions.

When a crack travels toward an older crack at some angle other than 90 degrees, it comes under the stress that is parallel to the sides of the old crack. The distribution of stress around the tip of the new crack becomes asymmetric. The new crack changes its direction of travel so that the angle between the cracks gradually increases to 90 degrees when the cracks join. The new crack then ends.

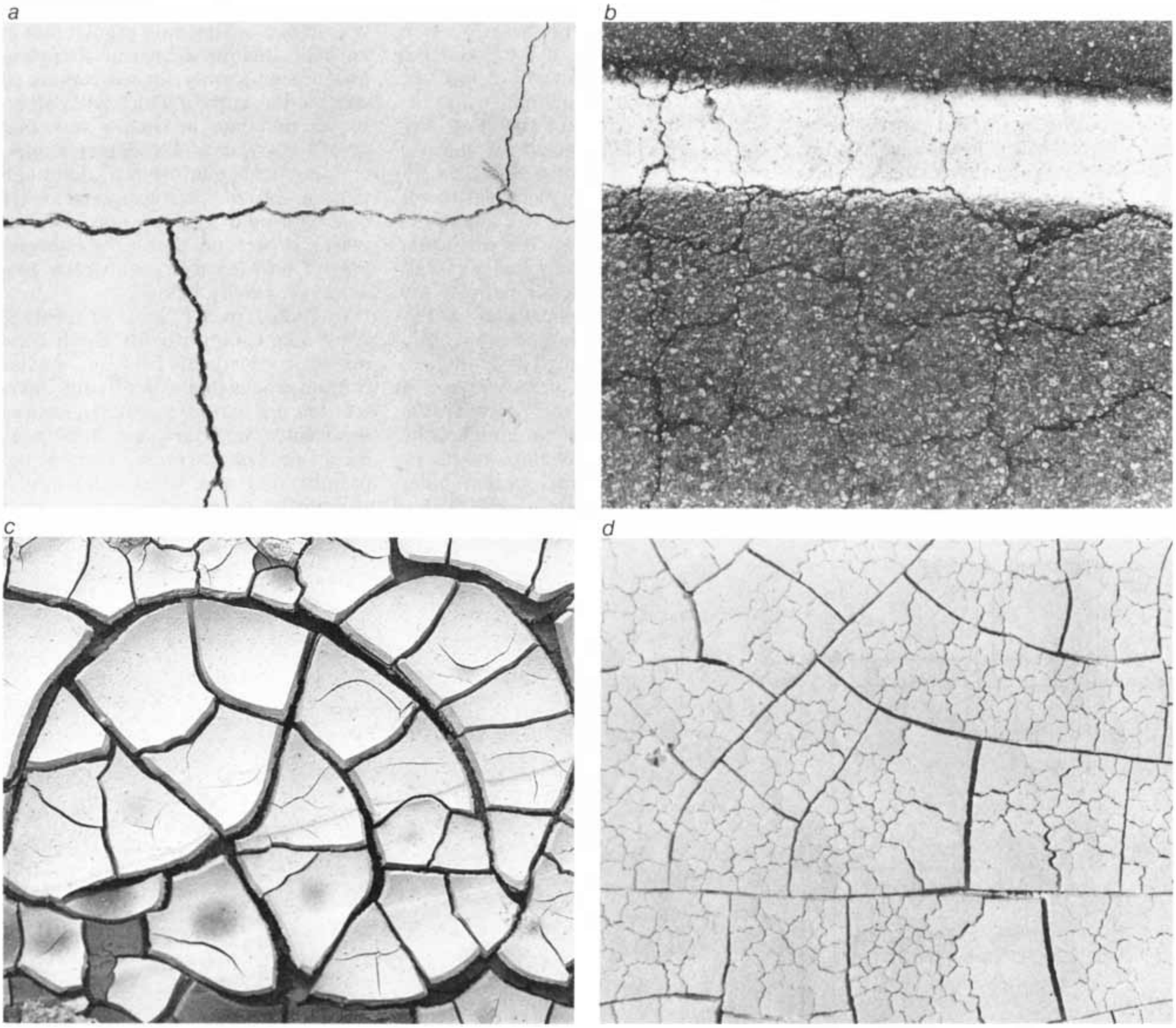
With these general rules you can often determine the history of a crack network. Pick out a long, more or less straight crack that has many intersections. The side cracks that extend from it but do not reach another crack must have been formed by the stress parallel to the faces of the main crack. The side cracks that intersect other cracks either began on the main crack or traveled there. In both cases the intersections with the main crack are perpendicular to it.

To make a record of how the network formed draw a map of what appear to be the oldest cracks. The islands they create are large and quite likely four-sided because of the perpendicular intersections. Add the side cracks. They create smaller islands, which are probably four-sided also. In a complex network of cracking you might be able to discern several generations of cracks.

In 1962 Arthur H. Lachenbruch of the U.S. Geological Survey classified polygonal crack networks in terms of their dominant intersection angle. One class contains all networks with nonperpendicular intersections. The networks with perpendicular intersections are grouped according to whether they are randomly formed or are oriented because of an asymmetry in the stresses producing them. The randomly formed group is further classified as having either irregular or regular polygons according to whether the sides of the polygons are sinuous or approximately straight. In some cases a network that begins as a system of irregular polygons may develop enough additional cracks to become a system of smaller regular polygons.

I surveyed many crack systems. On a tennis court I found cracks that developed when ground pressure forced the playing surface upward, putting it under tensile stress. The stress produced sinuous cracks with 90-degree intersections that created large polygons, most of them four-sided. A few of the intersections formed small triangular islands. A triangle may form when two nearby side cracks from the main crack curve toward each other, intersect and then continue as a single crack. A triangle may also form when two cracks intersect at some angle other than 90 degrees and new stress adds a short third crack.

Polygonal-crack networks were also evident in blacktop road surfaces, but the polygons were typically smaller than the ones on the tennis court and more of the intersections were at angles other than 90 degrees. Again the



Cracks in a tennis court (**a**), *pavement* (**b**), *mud* (**c**) *and cornstarch* (**d**)

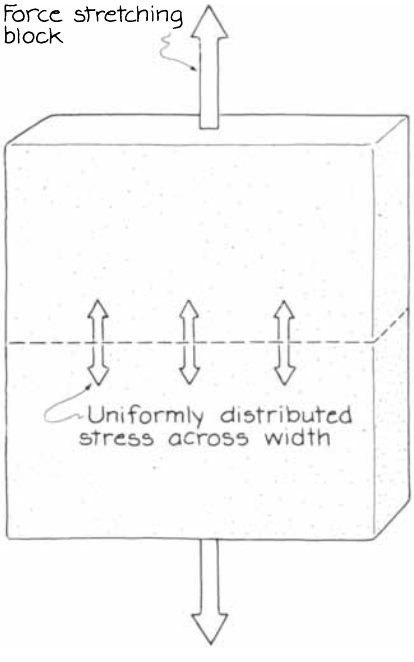
Columnar cracks in Giant's Causeway, Northern Ireland cracks were noticeably sinuous. Some of them were curved, presumably because they changed directions when they approached older cracks. (Crack production in road surfaces is complicated by the fact that a passing automobile displaces developing islands. Water creates additional stresses when it freezes and expands in the cracks.)

Many concrete slabs display cracks and crack networks. Cracks develop where the slab buckles because of its weight or the stresses induced by a shifting support. Although many intersections are perpendicular, many are not, presumably because the stresses are complex and may be influenced by the shape of the slab, particularly if the slab is small.

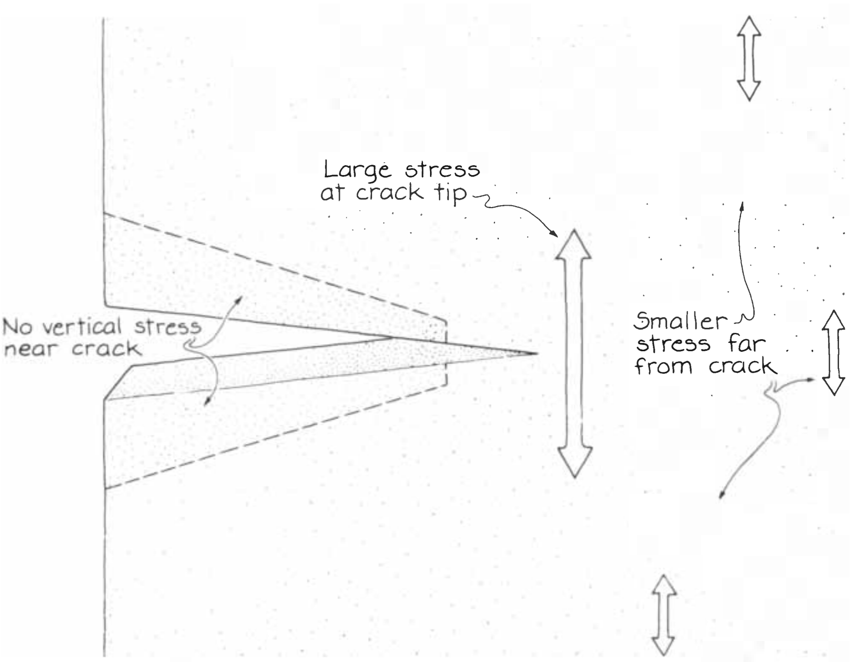
Crack networks develop in drying mud as the water between grains evaporates. Forces on the grains tend to contract the mud surface, giving rise to cracks. One source of these forces is the surface tension of the water between the grains. As water is lost, the top surface of the remaining water becomes concave and pulls on the grains. If the grains have electrically charged surfaces, they may also be pulled toward one another by electrical forces between those surfaces and any molecules in the water between them that are oriented by the charged surfaces. The resulting contraction puts the top layer of mud under tensile stress. Every small region is simultaneously pulled horizontally in all directions.

The tensile stress increases until it cracks the mud surface. Many cracks may appear almost simultaneously. Then side cracks develop in the islands. When the cracks meet older cracks, smaller islands are left. Theoretical calculations of the energy involved in cracking mud predict that in an ideal situation the tensile stress will produce uniformly spaced centers of contraction, each of which will pull on its surroundings in such a way that cracks intersect at 120-degree angles, creating hexagonal islands. Although photographs of such hexagonal arrays can be found in textbooks and research papers, nearly all the intersections I have seen in mud-crack networks are perpendicular.

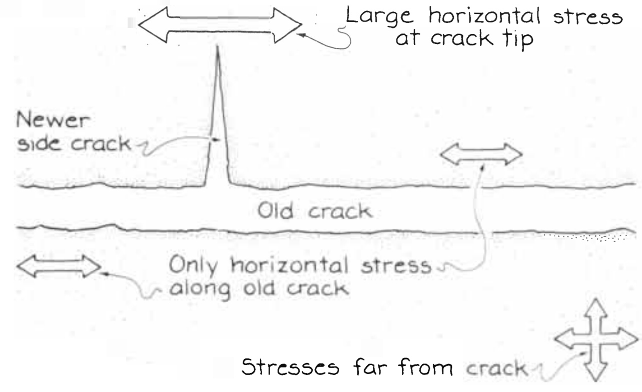
In 1966 James T. Neal of the U.S. Air Force Cambridge Research Laboratories concluded from his studies of mud cracks that as a rule the intersections are indeed perpendicular and the islands are four-sided. Why does theory predict otherwise? Perhaps the premise that mud dries uniformly is unrealistic. In my observations mud



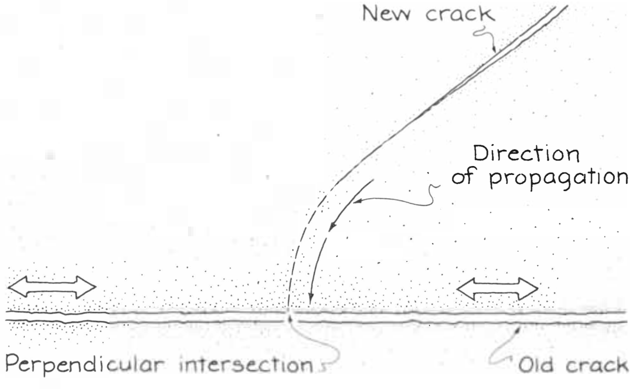
Tensile stress in a block



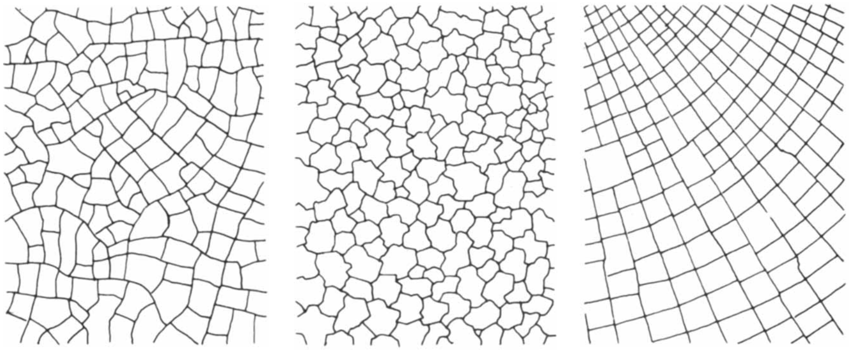
Stresses near the tip of a crack



How a side crack forms



An intersection of cracks



Random and regular

Random and irregular

Oriented

Perpendicular-crack networks

initially cracks in random places, relieving a stress in some complicated way. Newer cracks then travel through material that is no longer under uniform tensile stress. When they approach the older cracks, they must turn to make perpendicular intersections, creating four-sided polygons.

I think another factor may account for hexagonal networks. I have explained crack propagation as being due to pure tensile stress, a fracturing condition sometimes called Mode I. There are also modes II and III. Imagine a three-dimensional mud crack with a tip several millimeters deep. Mode II fracturing results when the two faces of the crack slide horizontally past each other. In Mode III fracturing the faces slide vertically. Both modes create shearing with no separation of the crack faces.

Mode II seems to me to be more likely in mud cracking. When an initial crack opens in the mud, it may put an adjacent region under shearing stress. The region is already under tensile stress. The combination of stresses forces the crack into the adjacent region but in a new direction, possibly at an angle of 120 degrees to the initial direction. If fracturing continued in this way, the crack pattern would be hexagonal.

Neal also studied the giant networks of sinuous cracks revealed by aerial photographs of playas and deserts. The cracks developed after decades of drought had lowered the water table in areas of clay or sandstone. Some of the polygons are 100 meters across. The fissures, which are generally V-shaped, can be more than a meter deep. Here again the dominant angle at intersections is 90 degrees.

In networks of mud cracks the top layer of each island may curl upward. In 1928 Chester R. Longwell published a study of such mud curls. As the layer dries and contracts, it separates from an underlying sandy layer. If the evaporation is rapid, the top surface of the layer shrinks faster than the bottom surface, and the resulting stresses within the layer force its perimeter to curl upward. Depending on the rate of evaporation and the type of grain, it may curl until it becomes a cylinder no wider than a pencil.

Longwell described fine clay material as being ideal for this extreme curling, presumably because it contracts so much when it is dried. Silt develops only concave plates; when sand is mixed into clay or silt, there is no curling. If there is an underlying bed of sand, a thin top layer of clay or silt may separate from it. Hence curling can be found in regions where a recent rain has washed a thin layer of clay or silt over a sandy or hard bed. I find curls when a thin layer of mud dries on my stone patio.

I examined crack networks in a solution of cornstarch that I mixed by hand in a large, rectangular baking dish until all lumps were gone. After several hours a layer of water had separated from the solution. I removed it with a rolled paper towel that I dipped into the water and hung over the side of the dish.

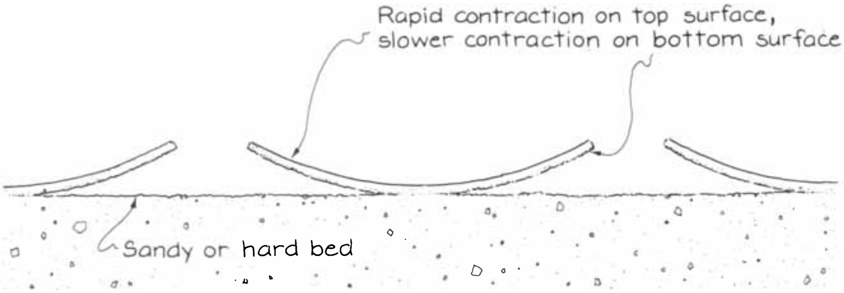
When I examined the dish a few days later, the cornstarch looked dry, but it had not cracked. Then, within an hour, several large cracks appeared across the length of the material and smaller ones appeared at the edge. Their paths were obviously influenced by the shape of the dish. The cracks that subsequently formed in the isolated islands were independent of the dish shape. Often they curved to intersect at right angles with older cracks, which were widening continuously with further shrinkage of the material. Some of the polygons began to curl upward, but later they flattened out.

With the end of a paper clip I poked a hole in the middle of an island. The surface was brittle, as was shown by the fact that three cracks developed immediately and traveled away from the hole for several millimeters. Within minutes these new cracks lengthened until they joined older ones. One of them curved almost 90 degrees to make its intersection. Crack formation continued for another day, leaving many four-sided islands. Next, within an hour every island ruptured into fine-scale polygons outlined by shallow, sinuous cracks. The cracking then stopped. The network had begun with regular polygons; it ended with irregular ones.

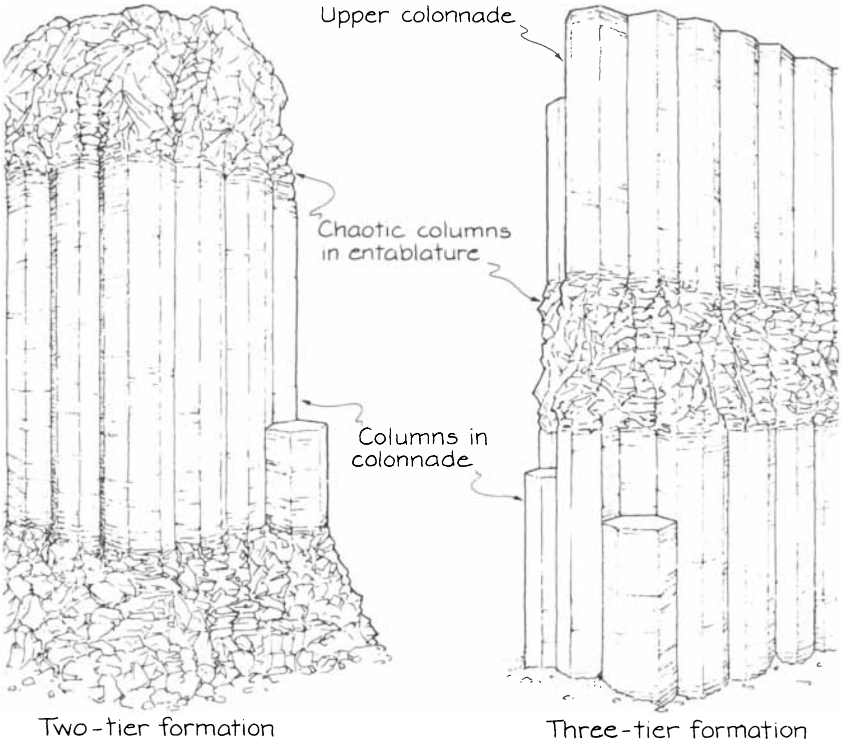
The crack networks in the basalt fields of Giant's Causeway, Devil's Tower in Wyoming, Devil's Postpile in the Sierra Nevada, Fingal's Cave in Scotland, the Boiling Pits in Hawaii, Mount Etna in Sicily and those in many other places are remarkably different from the others I have discussed. They appear to be due to lava flows that formed pools and whose top and bottom surfaces then cooled rapidly. The interior of the flows took years to cool and solidify. The stresses induced by contraction as the material cooled made the interior fracture into polygonal columns.

At Giant's Causeway weathering has exposed many horizontal and vertical faces of the crack network. In some places the fracture has left a two-tiered vertical arrangement. Near the bottom of the basalt are stately columns up to 20 meters in height. Their cross sections are distinctly polygonal, many of them appearing as hexagons. The average width is about 70 centimeters. Above this "colonnade" is an "entablature" consisting of smaller, less well formed and often chaotic columns. In other places a three-tiered arrangement is seen: above the entablature there is another colonnade made up of columns that are almost as impressive as those in the lower colonnade. The transition between adjacent tiers is abrupt, although there is no evidence of any change in material content across the transition. The transition line can run for quite a distance horizontally, implying that whatever was happening to cause the transition at one point was happening everywhere at the same level.

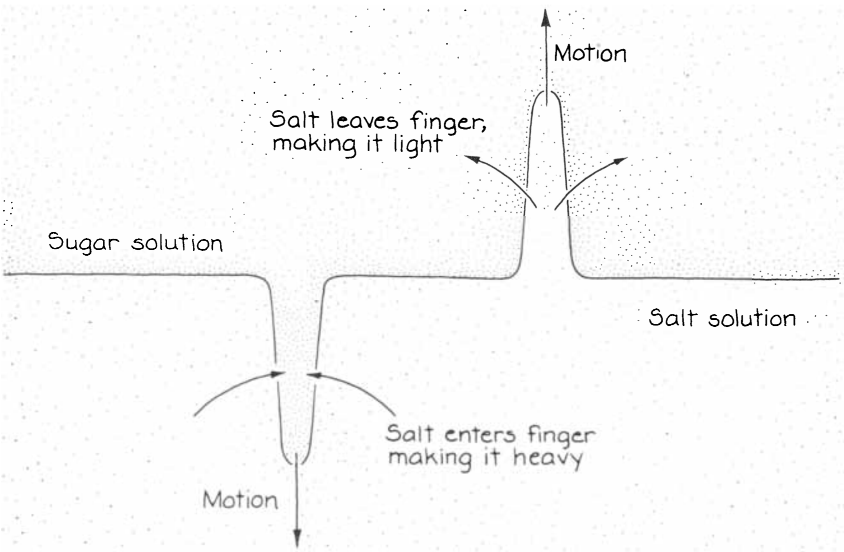
These formations present two enduring puzzles. Why should rupturing create splendidly shaped columns in the colonnades and irregular ones in the entablature? Why is the transition between tiers so sharp and so extensive horizontally? For hundreds of years scholars have proposed varied theories to explain these lava formations. Among the more recent ones are an idea put forward in 1978 by Michael P. Ryan and Charles G. Sammis, who were then at Pennsylvania State Uni-



How mud curls form



Structure of the columnar basalts at Giant's Causeway



Salt fingers as an analogy of crack formation in basalt

versity, and another idea advanced by Lakshmi H. Kantha, then at Johns Hopkins University.

Ryan and Sammis considered the solidification of a pool of lava. As a pool solidifies, the upper and lower interfaces between the solid and the liquid move slowly into the interior. As the upper interface progresses, for example, a cooling solid layer is left above it. Contraction that accompanies the cooling process puts the layer under tensile stresses that build up until the layer suddenly ruptures into a network of cracks.

In 1959 the Kilauea volcano in Hawaii filled a crater with lava to a depth of more than 100 meters. Observations by means of boreholes indicate that the upper solid-liquid interface is descending at the rate of about one centimeter a month. Occasionally shock waves are recorded. They can even be felt and heard when one walks on the now solid top surface. They seem to result from the sudden fracturing of a solid layer just above the interface. The layer appears to be no more than .5 meter thick when it fractures.

In such a case the theoretical calculations that predict a trend toward hexagonal polygons may be applicable. As the solid-liquid interface continues to descend, the crack network may follow it, thereby forming columns. Ryan and Sammis worked out details of how the process might operate. They argued that the cracks propagate vertically by means of a combination of Mode I and Mode III fracturing. Indeed, there seems to be evidence of such propagation along the length of the columns they examined at Boiling Pits. Although the explanation may be correct, it fails to account for the formation of tiers or their knife-edge transitions.

Could some feature of the liquid leave its trace in the solid and thus influence rupturing and the subsequent formation of columns and tiers? Bénard cells are a candidate. Under certain conditions a liquid heated at the bottom or cooled at the top can develop hexagonal convection cells with fluid rising within the cells and descending at their perimeter. Bénard cells, however, are short in relation to their width—nothing like the long, thin columns in basalt.

In 1981 Kantha noticed that the tiering in basalt resembles the fluid-flow phenomenon called salt fingers. The fingers are thin columns of fluid that form at the interface between two solutions because of a difference in the diffusion rate of the molecules in the solutions.

With patient work you can demonstrate the phenomenon in your kitchen. Get a transparent container, preferably rectangular in order to avoid refraction of light by curved surfaces. Mix salt into water several centimeters deep. In another container with a pouring lip mix a sugar solution in about the same amount of water. Add a drop of food coloring. Pour the sugar solution slowly onto a spoon held just at the top of the salt solution. The sugary liquid mixes gradually with the salty one. The density of the sugar solution should be slightly less (specific gravity 1.1) than that of the salt solution (1.12), in which case the sugar solution should spread into a layer over the salt solution.

Although the distribution of densities is stable, the arrangement becomes unstable with any small disturbance of the interface. Suppose the interface bulges upward. The bulge contains salt solution. Because salt diffuses faster than sugar, salt diffuses from the bulge into the surrounding sugar solution faster than sugar diffuses into the salt. The bulge becomes lighter than the surrounding solution and moves upward. As the process continues, the bulge becomes a finger.

An hour or two after you pour the sugar solution the interface develops short columns, each a millimeter or less in width. Above and below that region the solutions are mixed by convection. With time the columns grow longer, wider and better defined and develop polygonal cross sections. The transition between the columns and the mixing layer above it resembles the two-tier formation in basalts.

A three-tier formation can be made if the density of the salt solution decreases with height. You will observe a middle layer where the mixing is turbulent. Above and below it are columnar layers. (In both demonstrations you can see the columns better if you stand a meter or so away from the container and move your head to the left and right so that the refraction of light by the columns produces a weak scintillation.)

Kantha hypothesized that fingers in lava gave rise to the fracture network seen in columnar basalts. When the basalt solidified, cooled, contracted and cracked, the cracks tended to follow the edges of the polygons that were formerly the fingers. The cracks then traveled vertically as the crack network followed the solid-liquid interface. The exciting aspect of this explanation is that it neatly explains the knife-edge transitions between tiers in the basalts. They mark the ends of fingers. Was Kantha right? Work now being done seeks to test the explanation and to show how fingers could form in molten basalt.

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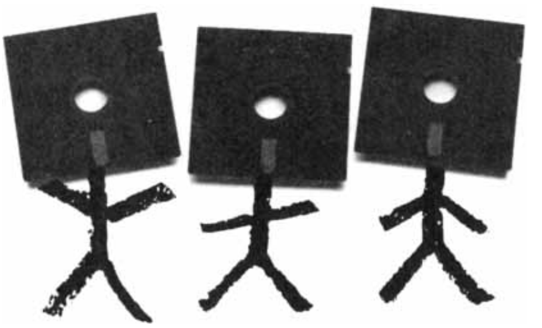

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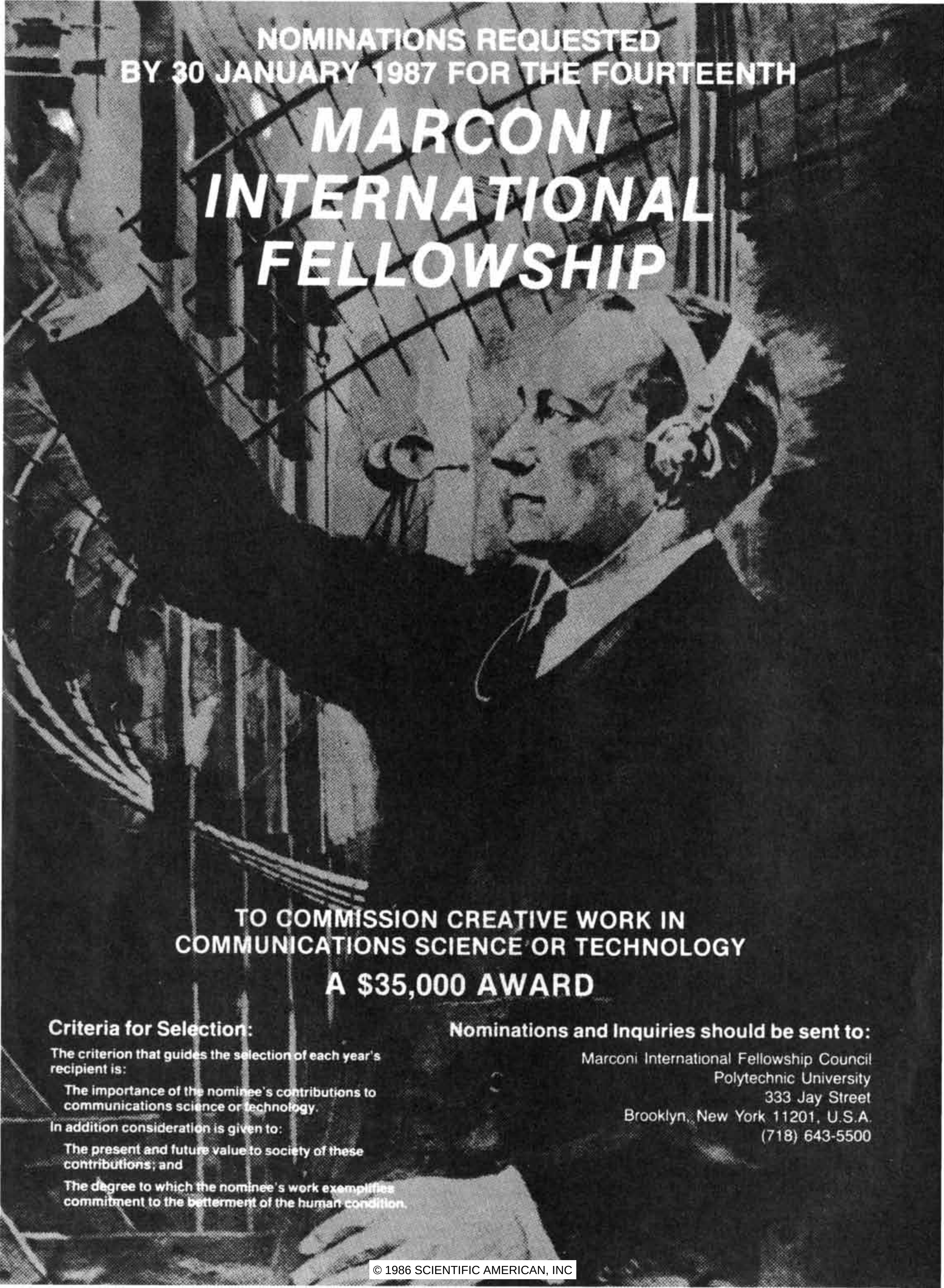

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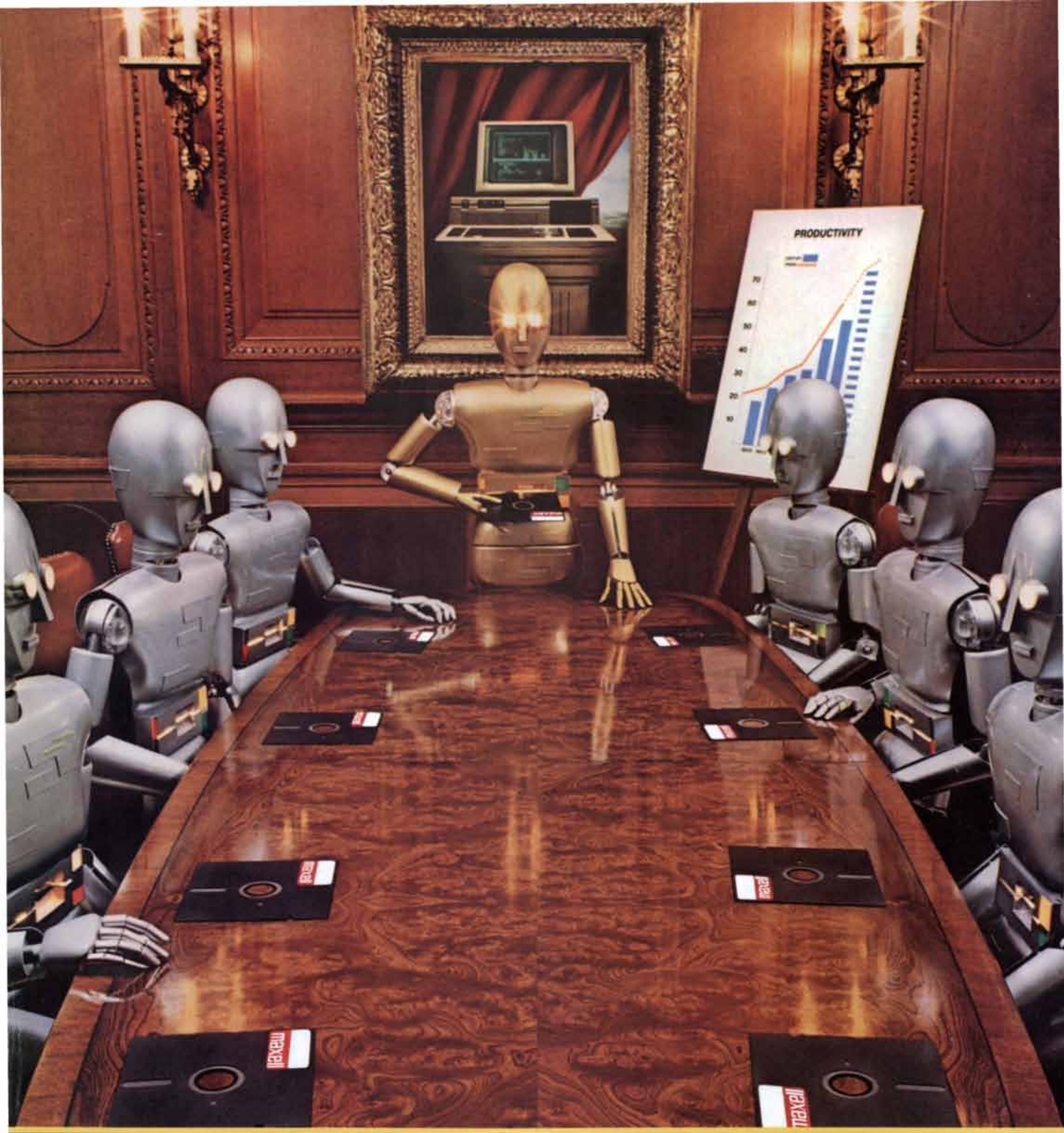
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