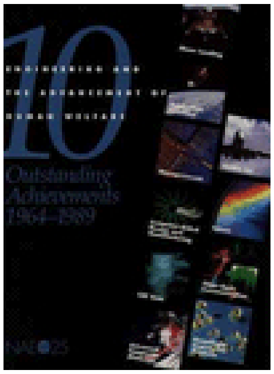

Engineering and the Advancement of Human Welfare: 10 Outstanding Achievements 1964-1989

National Academy of Engineering

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10 Outstanding Achievements 1964–1989 ENGINEERING AND THE ADVANCEMENT OF HUMAN WELFARE

Selected by the National Academy of Engineering on the occasion of its 25th anniversary December 5, 1989

NAE 25

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Introduction

The years 1964 to 1989, the first 25 years of the National Academy of Engineering, have witnessed more advancement in technology and, consequently, greater change in the lives of people than any previous 25-year period in recorded history. As part of its anniversary celebration, the Academy has selected what it considers to be the 10 outstanding engineering achievements that have reached the public since the Academy's founding on December 5, 1964. Each represents a major advance or breakthrough in engineering and a significant contribution to human welfare.

This brochure presents each of the 10 achievements in a separate story, where we share with you some of the engineering challenge, insight, and excitement that attended the achievements. In doing so, we hope also to convey a better understanding of what engineering does and how it has contributed to human welfare over the past quarter century by improving our lives, extending our possibilities, and expanding our horizons.

Members of the Academy and representatives of several professional engineering societies submitted suggestions of outstanding engineering achievements. More than 340 suggestions were reviewed by the NAE Advisory Committee on the 25th Anniversary Celebration. The Council of the Academy approved the top 10.

No such list can encompass all the technological advances important to society; many other engineering accomplishments nearly made our list. The Indus Basin Scheme and its Tarbela Dam, for instance, bring flood relief and stable water supply to millions in Pakistan. The entirely new cities of Jubail and Yanbu—ports at either end of the crude-oil pipeline across Saudi Arabia—gave modern living conveniences to tens of thousands of people in the desert. The Alaska pipeline, deepwater oil platforms, and drilling technologies help supply much of our energy need. Auto emission control systems, including the catalytic converter, and processes for vitrifying hazardous waste—sealing them in glass for long-term storage—provide additional protection for our environment. Artificial hearts, cardiac pacemakers, and orthopedic implants give new life to thousands of people.

The top 10 achievements are presented here in nearly chronological order. In some cases we have grouped related achievements. For instance, lasers stimulated the development of fiber-optic communication, so we placed them together. And we chose to lead the list with the moon landing, which is truly one of the outstanding engineering achievements of all time.

The most striking aspect of these 10 diverse achievements is how closely they are tied together. The microprocessor, which has probably had the widest impact of all, has contributed to the development of today's application satellites, the CAT scan, computer-aided design and manufacturing, as well as genetically engineered products. Modern jumbo jets benefit from microprocessors, computer-aided design and manufacturing, lasers, fiber-optic communication, advanced composite materials, and application satellites. In turn, many of these achievements are closely tied to earlier, sometimes seemingly unrelated advances in the basic sciences, including mathematics.

It is also striking how widely and deeply these engineering advances have affected our daily lives. Weather satellites, which have been routinely used only since 1966, generate the satellite pictures seen on almost every television weather report. The microprocessor, invented in 1971, operates toys, televisions, videocassette recorders, microwave ovens, and burglar alarms in probably the majority of U.S. homes. Advanced composites, which first appeared in commercial products in 1973, are now used by most people who golf, ski, or play tennis. And every telephone call of any distance is undoubtedly carried on beams of laser light flashed through fiber-optic cable, a service that has been commercially available only since 1977.

Because some engineering achievements are often viewed as sources of environmental degradation, it is important to note the beneficial effects many of these 10 have had on the environment. For example, the famous pictures of the earth taken by Apollo astronauts on their moon flights vividly show us how delicate and small our planet is compared with the forbidding immensity of space. Photos from Landsat and other earth-observation satellites for the first time have given us a good look at our fragile global environment, pinpointing areas needing help. And microprocessors, by improving the efficiency of everything from cars to power plants, help conserve scarce natural resources and greatly reduce the amount of pollutants released into the environment.

The next 25 years will witness even more advances in technology, bringing ever-greater changes to our way of life. It is therefore important, if we are to ensure the wise use of technology, that all of us—engineers and nonengineers alike—understand the nature of engineering and how it can be used to benefit us individually and as a society.

Finally, it is obvious that many more fascinating challenges for engineers lie in the future. We've built CAT scans and other wonderful machines that peer into the unopened human body, but can we develop devices and techniques that perform a total chemical analysis of the body without breaking the skin? We've used microprocessors to make soda machines talk, but can we use them to make computers really think before they speak? And yes, we have been to the moon, but what about going to Mars? The engineering achievements of the future are limited only by the laws of nature and our own imagination.

ROBERT M. WHITE
President

1

Moon Landing

Six hundred million people— nearly one-fifth of the world's population—watched on television in July 1969 as an earthling first set foot onto another celestial body. With that step, human consciousness leaped a quarter million miles into space, expanding mankind's vision to a degree unequalled since Columbus's voyage to the New World. “The astronauts didn't just go to the moon,” said one observer. “All our minds went to the moon.”

Looking back from the moon, people saw white wispy clouds and blue sparkling water covering a planet framed by immense darkness. Earth appeared as a highly integrated unit, not just a collection of isolated oceans and continents. And it was strikingly obvious how small, fragile, and beautiful our planet really is, a precious oasis in the vastness of space.

The Apollo program sent nine spacecraft to the moon from 1968 to 1972, landing a dozen astronauts at six different sites. The rocks and scientific information they brought back revealed that the moon was formed at the same time and of the same elements as earth but that it lacks water, atmosphere, and life. The astronauts also left instruments to gather data on ground tremors and other phenomena. A laser reflector left by *Apollo 11* astronauts is still being used to measure the earth-to-moon distance and study the movement of continents.

Right: The first steps of an earthling on another celestial body are recorded in moon dust.

The feat of landing men on the moon and returning them safely home ranks the Apollo project with the Egyptian pyramids, the Panama Canal, and the Manhattan Project as outstanding engineering achievements of all time. It stands alone for the advances in size and sophistication it made over prior technology. Apollo required a rocket 15 times more powerful, a navigation system far more reliable, a unique lunar landing craft,and improved space suits capable of withstanding a very hostile environment. In addition, the program demanded a novel, comprehensive management system to ensure that thousands of government and industrial organizations worked together well enough so that millions of parts would arrive where they should on schedule and would fit and function properly.

***Apollo 17* is readied for a nighttime launch toward the moon, peeking out from the clouds beyond. The spacecraft carried the first scientist to the moon and was the only one launched at night in the Apollo series.**

The Saturn/Apollo system was composed of an Apollo spacecraft, a lunar lander, and a three-stage Saturn V rocket, which launched them toward the moon. Once in lunar orbit, the spacecraft released the two-stage lander, which carried two of the three astronauts to the surface. The lander's ascent stage later returned them to the spacecraft and was abandoned. Just before they reentered the atmosphere, the astronauts jettisoned the large service unit that supplied power, water, and oxygen and returned to earth in the small command capsule of the spacecraft.

An*Apollo 11* astronaut unpacks a scientific experiment to measure ground tremors on the moon. The small laser reflector, on the ground behind the astronaut, is still being used for laser measurements of the distance between the earth and moon.

Buildings shook and the ground trembled when a Saturn V rocket roared skyward with the first trio of astronauts heading for lunar orbit in December 1968. The rocket developed roughly enough thrust to hurl a small house into earth orbit. Thirty-six stories tall and weighing as much as a good-sized Navy destroyer, the Saturn/Apollo vehicle used the biggest, most powerful rocket ever built.

The first stage of the three-stage Saturn V dwarfed the largest rockets of its day. An Atlas ballistic missile, for instance, produced 360,000 pounds of thrust. The first-stage engines of the Saturn V, however, each produced 1.5 million pounds, and there were five. Together they burned 3 tons of kerosene and liquid oxygen per second. Building reliability into such monstrous engines was a monumental challenge. Yet, all 12 Saturn V rockets launched in the Apollo series succeeded.

To fuel the second and third stages, engineers chose liquid hydrogen, which gave 40 percent more thrust per pound of fuel burned than kerosene. The second stage was a cluster of five engines, while the third had just one. But unlike those in lower stages, the third-stage engine had to be restartable in order to push the spacecraft toward the moon after coasting an hour and a half in earth orbit.

Building a rocket of such size and design required many new and advanced engineering techniques. The field of fracture mechanics, for example, advanced greatly in answering questions raised during construction of the second-stage fuel tank, which was 65 feet long, 33 feet in diameter, and held liquid hydrogen at −423 degrees F. The aluminum tank was pieced together with literally miles of welds, which could contain a few tiny cracks. But how big could the cracks be before they began to weaken the tank? By analyzing aluminum with similar cracks, engineers calculated the amount of pressure the metal could stand before cracks of various sizes begin to grow and thus become dangerous. To ensure its safety, they tested each second-stage tank by loading it with liquid hydrogen at a pressure 5 percent higher than the maximum required for flight. If cracks did not grow at that pressure, they would not grow at the lower pressure during flight.

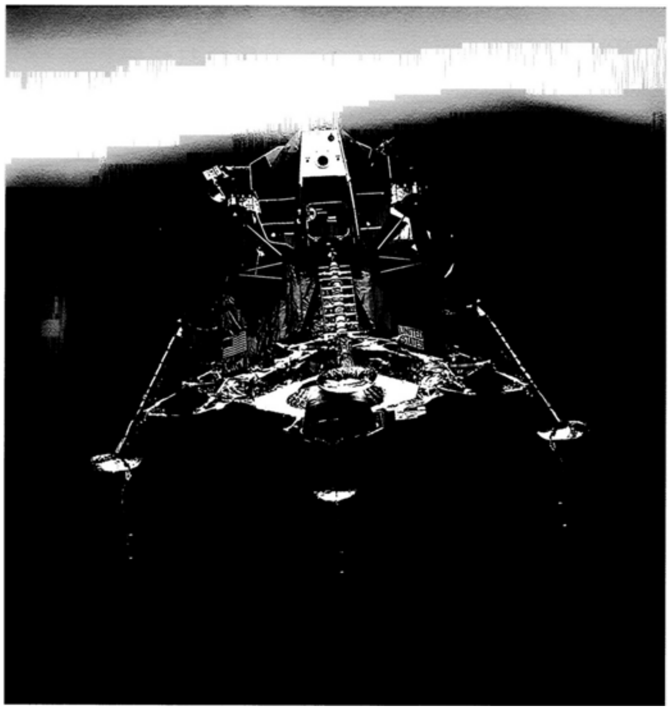
The Apollo flights would have been impossible without inertial navigation, which was developed in the 1950s and was just being installed in the early 1960s on aircraft, submarines, and ballistic missiles. Radio navigation from earth was impractical during the final minutes of a landing approach to the moon. The time radio signals take to travel that distance is too long for the immediate reactions needed to land a craft safely. Radio navigation was also useless for flights behind the moon because it requires line-of-sight transmission from earth.

The five first-stage engines of the mighty Saturn V rocket lift *Apollo 11* off the launch pad and start the spacecraft toward the moon. Astronauts are in the conical command capsule atop the rocket. Just below the capsule is the cylindrical service unit. Below that, the lunar lander is packed in another cylinder just above the rocket's third stage.

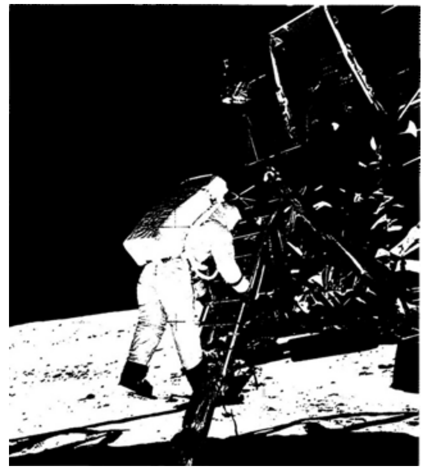
Apollo's navigation—the rocket, spacecraft, and lunar lander each had a separate system—included gyroscopes and accelerometers, which sensed change in direction and speed. They were combined in single subsystems, called inertial measurement units, or IMUs, which measured movement along, as well as off, the desired course due to rocket thrust or atmospheric resistance. When leaving or approaching the earth or moon, IMUs were critical for making quick guidance decisions. Gravitational influences of the earth and moon were calculated before flight and added to onboard guidance computers. This information and the IMU data permitted control systems to keep the craft almost exactly on course. During the flight, astronauts used a sextant in calculating midcourse corrections. In practice, however, ground radar stations usually performed this time-consuming task and radioed up commands to correct deviations.

The two-stage lander that ferried astronauts to the lunar surface was the first manned vehicle designed to fly solely in space. Its structure could be extremely lightweight, since the moon's gravity is only one-sixth that of earth. And aerodynamics did not need to be considered, since there is no air on the moon. The lander was essentially built inside out. Its thin aluminum pressurized cabin was inside, wiring and tubing surrounded that, and a patchwork of black or golden insulating materials covered the outside. These materials absorbed or reflected light, depending on whether that part of the lander needed protection from cold or heat. Its four spiderlike legs with wide foot pads could keep the lander upright, whether it touched down on a slope, in deep dust, or under any of 500 other combinations of terrain and landing conditions anticipated by the engineers.

One of the most critical parts of the lander was the small ascent engine. Once the astronauts landed, they were completely dependent on this engine to return them to the mother ship. There was no backup. The basic portion of the flight engine had been briefly test-fired on earth. Its fuel system, however, had not previously been exposed to the highly corrosive propellants for fear of weakening its seals and corroding its valves. So engineers ground-tested ascent-engine prototypes for every failure they could imagine that might happen in flight. None did.



The lunar lander, seen from the *Apollo 11* spacecraft, heads for a landing on the moon. The descent stage, with outstretched legs and protruding rocket nozzle, will remain on the moon when the upper ascent stage brings the two astronauts back to the mother ship.



Right: Dressed in a three-piece space suit, an *Apollo 11* astronaut climbs down a leg of the lunar lander and hops onto the hard, dusty surface of the moon. His life-support back pack carried enough oxygen for a 4-hour tour outside the lander.

Astronauts who walked on the moon wore a three-piece space suit and backpack of life-support equipment for up to four hours outside the lander. The ensemble weighed 190 pounds on earth but only a sixth of that on the moon. The first piece was a cooling undergarment of knitted nylon-spandex with a network of plastic tubes filled with water circulating from the backpack. The next piece was the basic suit, a rubber-coated nylon bladder sandwiched between a cloth lining and a nylon cover to shape the suit. The third piece was a protective outer garment of 17 layers, including 6 layers of Beta cloth. This is a fireproof fabric of fiberglass threads coated with Teflon to prevent itching. The outfit was completed by a helmet, boots, gloves, and the backpack, which also carried a radio and antenna.

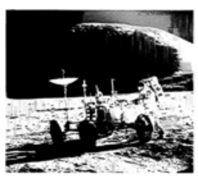
The Apollo program was probably the most complex and ambitious engineering project ever attempted. A moon flight required more than 450 persons in the launch control center and nearly 7,000 others on 9 ships, in 54 aircraft, and at stations around the world. At its peak, 400,000 people were working on Apollo at three major space centers and 20,000 contractor sites. The people who managed Apollo pioneered techniques that remain the model for operating a massive, well-run engineering program. In 1961 NASA estimated that the project would cost $20 billion and would put a man on the moon before 1970. The space agency actually spent $25.4 billion for all the Apollo flights. And two *Apollo 11* astronauts stepped onto the moon on July 20,1969.

On the planning and control side of the program, the Apollo managers created a monitoring system that gave them enough information to ensure that the millions of pieces for the project were coming together at the right time and place, in the right engineering configuration, and for the right price. To do this, they identified a few hundred critical milestones—such as "rocket first stage complete" or "stage shipped to Cape Kennedy"—for each program area. Once a month, contractors reported their progress to the three NASA centers, who reported to the Apollo managers. The managers, in turn, identified projects that were falling behind—most of them did—and devised solutions to bring them back on schedule. For instance, when a tragic fire killed three astronauts during a ground test of their spacecraft, managers swiftly reviewed the safety of nearly the entire Saturn/Apollo system, redesigned the spacecraft and space suit, and brought the program back on schedule in little more than a year.

On the technical side, the great challenge was to create a management system that would ensure the precise interface among millions of pieces—the Saturn V alone had 6 million—manufactured by thousands of contractors. Careful records were kept of specifications for all the parts and the interfaces between them. This documentation was especially valuable when, for instance, during the unmanned second Apollo flight, the first-stage engines began to flicker, a piece of an aluminum panel fell off, and two second-stage engines quit early. By comparing flight instrument data with the documentation, engineers were able to find the problems, simulate them on the ground, and correct them with enough confidence to go ahead with the next flight—the first with astronauts aboard.

The earth, like a sparkling jewel against black velvet, rises above a barren lunar landscape to greet the *Apollo 11* astronauts 240,000 miles out in space.

The first two moon flights—*Apollo 8* and *10*—put astronauts into lunar orbit; *Apollo 11* and *12* put them on the moon. An exploding oxygen tank in the service unit crippled *Apollo 13*, whose astronauts took temporary shelter in the lunar lander during the emergency return to earth. *Apollo 14* went smoothly. During the next three missions, astronauts traveled over the lunar surface in a motorized rover to gather rocks and conduct scientific experiments. *Apollo 17*, the last of the program, carried the first scientist—a geologist—to the moon in December 1972.



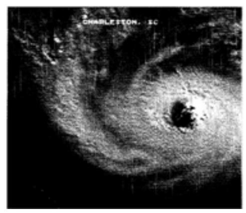
***Apollo 15* astronauts explore the moon in a lunar rover, which was packed aboard the lander and unfolded on the lunar surface. It carried the astronauts 17.5 miles during three exploratory tours and helped them collect 170 pounds of moon rocks for the return to earth.**

Since the inception of the Apollo program, nearly all the known planets in our solar system and many of their moons have been visited by unmanned spacecraft. Between them, the United States and the Soviet Union have sent automated probes to Earth's two neighbors, Mars and Venus, as well as to Mercury, the planet nearest the sun. U.S. probes have journeyed to all the other planets except Pluto. The most celebrated unmanned spacecraft, *Voyager 2*, left Earth in 1977, rendezvoused with Jupiter in 1979 and then with Saturn, Uranus, and finally Neptune in 1989. Yet, it was man's landing on the moon that truly captured the world's imagination, an engineering achievement that has extended the human domain far beyond the boundaries of earth.

2

Application Satellites

In November 1982, a U.S. weather satellite spotted a hurricane developing southwest of Hawaii and watched it start moving north. Suddenly the storm turned east and raked across the islands less than 24 hours later, leaving nearly a quarter billion dollars of damage in its wake. But only one life was lost. Hurricane warnings, based largely on satellite pictures, had alerted most people in time to take shelter.



The 125-mile-per-hour winds of Hurricane Hugo begin to lash the coast of the southeastern United States under the constant gaze of a U.S. weather satellite. Satellite images warned residents of Charleston (upper left) of the approaching Hugo, still 210 miles away in this picture, giving them several days to prepare for the storm and evacuate the city.

Twenty-five years ago, there were no operational satellites for weather forecasting or for any other routine application. Today, however, satellite systems girdle the earth watching for storms, relaying communications, mapping uncharted terrain, and helping ships and airplanes navigate anywhere on the globe.

Satellites started to become routine in April 1965, when the first nonexperimental commercial satellite flew into space and parked in orbit over the Atlantic. *Early Bird* carried circuits for 240 telephone calls or television service between Europe and North America. Today, several generations of satellites later, *Early Bird's* descendants handle up to 120,000 calls at once or share the capacity with TV broadcasts, computer data, and electronic mail. They are part of a worldwide communications network launched by the International Telecommunications Satellite Organization, or Intelsat, which now has more than 100 member nations.

Communications satellites have dramatically altered the nature of our global community. Twenty-five years ago, reliable communications existed only between countries in the developed world. But communications satellites and the development of small, portable television cameras have linked people together around the globe. In 1969, for example, communications satellites brought TV coverage of the first manned lunar landing—live from space—to nearly a fifth of the world's population. Today they bring instant coverage of news and events to every corner of the earth.

Scores of civilian and military communications satellites sit in a ring around the earth 22,300 miles above the equator. At that altitude they complete one revolution every 24 hours and therefore remain stationary relative to the surface of the earth below. Satellites in this geostationary orbit provide high sky platforms for relaying signals to and from ground stations, vehicles, boats, and planes scattered over the surface below.

The idea for a system of radio-relay satellites in geostationary orbit maintained by astronauts was described by science fiction writer and futurist Arthur C. Clarke in 1945. Astronaut custodians, however, were impractical and, when *Early Bird* went up in the 1960s, shown to be unnecessary. Transistors and other solid-state components of the satellite's innards were far more reliable than the vacuum tubes of 1945-vintage radios and small enough to fit into a tiny satellite. *Early Bird* lasted more than three years without maintenance, and today's communications satellites frequently last until their fuel runs out, about a decade.

An astronaut retrieves a communications satellite, *Westar VI*, that failed to go into high geostationary orbit after being launched into low earth orbit. The space shuttle brought the satellite back to earth, where it was refurbished. Pending U.S. government approval, the satellite will be launched aboard a Chinese rocket and will provide a communications link for East Asia.

A country divided by mountains, jungles, water, or distance is now often united by a domestic satellite communications system. In 1965 the Soviet Union established the Molniya system using satellites in oblong orbits looping over the northern latitudes. These satellites were not geostationary. However, one always rose above the country just as another set. Now more than 40 countries have established their own satellite communications systems, often by constructing ground stations and renting circuits on commercial satellites.

Communications satellites relayed live television coverage of moon missions to millions of people around the world. Here, *Apollo 15* astronauts collect rock samples.

Before the era of routine satellite use, weather observations were available for less than 20 percent of the globe. Much of the unobserved region covered the vast oceans of the Southern Hemisphere and the tropics, where a storm could churn into a hurricane with no one knowing until it sank a ship or washed away a town. But since 1966, when the first fully operational weather satellite system was launched, no major tropical storm has gone undetected anywhere in the world.

Two U.S. weather satellites circling from pole to pole scan the earth from low orbit twice a day. Soviet satellites also routinely survey global weather from polar orbit. High-flying satellites in geostationary orbit monitor wide reaches of the planet and generate the weather pictures seen on television. The United States launched the first such operational satellite, GOES (Geostationary Operational Environmental Satellite), in 1974 and now maintains one above the western Atlantic and another over the eastern Pacific. A European satellite hovers over Africa, an Indian satellite over the Indian Ocean, and a Japanese satellite over the western Pacific. These five provide continuous coverage of weather throughout the equatorial and midlatitude regions of the earth.

Two dish antennas near Bogota, Colombia, aim at a communications satellite in geostationary orbit above the equator.

Radiometers carried by weather satellites measure reflected solar energy and infrared energy radiating from the earth and atmosphere. Computers then turn the data into images of clouds and weather patterns. Radiometers also measure radiation at precise wavelength intervals, generating information that allows scientists to determine atmospheric temperature, water vapor, and ozone levels. Today's radiometers are sensitive enough to sound the atmosphere from geostationary satellites more than 22,000 miles up in space.

Weather satellites frequently carry equipment to relay data collected by thousands of remote automatic ground stations from instruments such as rain or river-flow gauges. And, since 1982, increasing numbers of U.S. weather satellites, as well as Soviet navigation satellites, have also been carrying search-and-rescue radio equipment, some of it supplied by Canada and France. The devices pick up distress calls from ships and planes in trouble, leading to the rescue so far of more than 1,200 persons.

Images generated by weather satellites have been used to study snow cover, geologic faults, and other large ground features. But the need for more detailed information gathered in a systematic, repetitive way led to the development of specialized terrainobservation satellites. These orbiters create high-quality images that can be used to help study worldwide crop production, search for minerals and petroleum, monitor environmental problems such as desert creep and deforestation, and measure snowmelt to predict water resources and control flooding. In 1972 the United States launched the first in a series of Landsat satellites, which scrutinize the entire earth from near-polar orbit, observing each spot at the same local time every 18 days.

All Landsats have carried multispectral sensors that measure solar energy and infrared radiation at four or more wavelengths. Every type of terrain reflects and absorbs sunlight and emits infrared radiation in ways that reveal its identity and condition. Objects often show up better at one wavelength than another, which gives this technique an advantage over conventional photography. The data are transmitted back to one of several ground stations, processed into images, and made available to the public. France and the Soviet Union have launched similar satellites and make their images available commercially. The French SPOT system produces particularly high quality images.

Infrared satellite images do not show as much detail as visible images, but they yield thermal information that the others cannot provide. Water, for example, that collects in faults usually holds more heat than surrounding rock. Infrared sensors detect this heat differential, revealing an otherwise hidden geologic formation. Infrared imaging is also useful for monitoring pollution, observing volcanic activity, and leading fishing boats to warm waters where fish might be gathered.

More recently, experimental terrain-observation satellites have been carrying microwave radar, which penetrates all types of weather, day or night. Microwave radar can, to a certain extent, penetrate leaves and is used to map jungle terrain. It can also penetrate dry sand and has been used to trace buried watercourses in the desert. Radar return signals also tell much about the land that is useful for mineral and petroleum exploration.

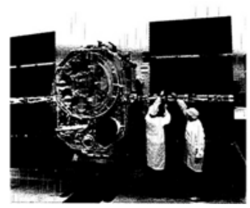
The military forces of the United States, the Soviet Union, and other countries use their own terrain-observation satellites to keep track of foreign troop movements, electronic communications, military installations, and rocket launchings. The satellites are hardier than their civilian counterparts, as well as more sophisticated, capable, and flexible. These “eyes in the sky” have greatly reduced the possibility for surprise attack and have thus helped maintain peace among world powers for the past quarter century.

In the future, satellites may be used to monitor the health of the entire earth biosphere. A major step in that direction will be taken as part of the International Space Year in 1992. A “Mission to Planet Earth” is being organized using earth-observation satellites and other means to study such problem areas as polar ozone holes, deforestation, ocean productivity, landcover change, and global warming caused by the “greenhouse effect.”

The precision of their orbits makes satellites ideal instruments for navigation. They have all but replaced the sextant since about 1968, when the Navy completed a system of navigation satellites, called Transit, for ballistic missiles fired from submarines. Transit employs satellites in near-polar orbits that are spaced to provide global coverage. Using data encoded on satellite signals, a computer-aided receiver on a ship or plane can determine its location to within less than a quarter mile.

Several satellites have already been launched for a new navigation system—the Global Positioning System (GPS), or Navstar—that will have 18 satellites plus 3 spares when completed. Using GPS, receivers in ships, planes, ground vehicles, and portable packs will be able to determine their locations to within 10 meters. The heart of the system is an atomic clock in each satellite that loses or gains just one second every 33,000 years. A plane, for example, receives signals from four satellites, each signal telling the time it was emitted and the position of the satellite. The plane's computerized receiver calculates how far each signal has traveled, then uses this data to pinpoint its position in space.

Satellite image reveals extensive clear cutting in Tongass National Forest on the northern tip of Prince of Wales Island, Alaska. Recently cleared areas appear pink, cleared areas that have started to recover are light green, and undisturbed forests are dark green.



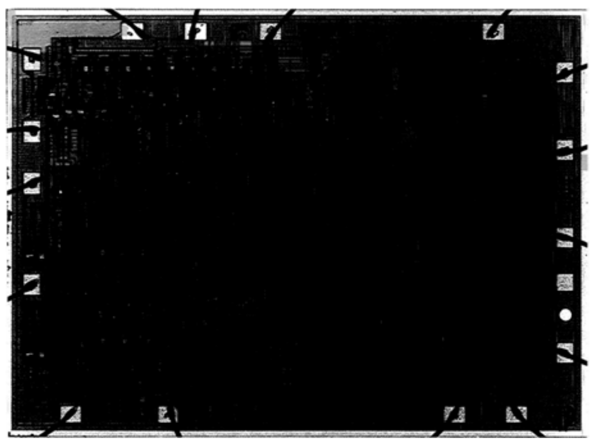
Technicians prepare a Navstar navigation satellite for launch. The 12 spike antennas will form the satellite's signal into a cone covering the entire hemisphere below.

In 1988 a satellite was launched to track long-haul trucks in the United States. A freight company using the system immediately found one of its trucks 300 miles off course. More advanced systems used by some military aircraft show pilots a map of the local area. Cars may someday be equipped to receive satellite signals that provide drivers with a street map of the city being traveled. Indeed, satellites may become our standard means of navigation, whether on land, in the air, or at sea.

3

Microprocessor

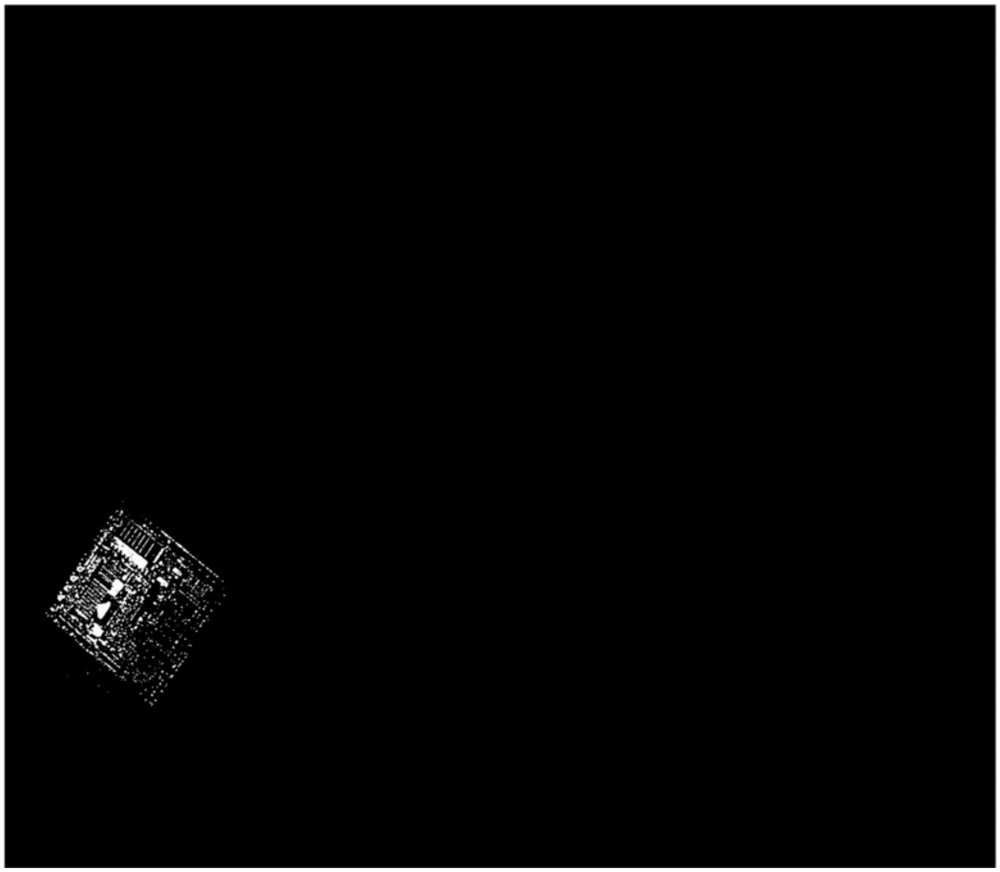
The microprocessor—a tiny "computer on a chip" no bigger than your fingernail— has quickly and quietly infiltrated our lives since it was introduced in 1971. At home, microprocessors are the brains in electronic devices that control microwave ovens and change television channels from across the room. At work, they help design complex buildings and control huge manufacturing machines. In between, they coordinate traffic lights and improve fuel efficiency in cars. And everywhere there is a personal computer, there is a microprocessor churning away inside.



A web of electronic circuitry spreads across the face of the 4004, the first *microprocessor*. The chip contains 2,300 transistors yet measures only 1/6 inch by 1/4 inch, about the size of a child's fingernail.

A microprocessor works something like a juke box's record player, which plays the tune on a record retrieved from its collection. A microprocessor, however, plays the set of instructions retrieved from a memory chip, performing simple functions—such as addition or subtraction—programmed into the instructions. Microprocessor and memory chips alike rely on microscopic integrated circuits to perform their tasks.

Before microprocessors, integrated circuit chips were generally not programmable. They could do only a single function for which they were designed, like a record player playing one tune engraved on its turntable. The first microprocessor, in fact, was developed by an American engineer who was given the task of designing 12 single-function chips for a Japanese calculator. Instead, the engineer designed one general-purpose chip that performed all 12 functions according to instructions stored in a memory chip. Because each instruction contained only four bits—the electronic 1's and 0's of digital code—the microprocessor was classified a 4-bit chip.



Microprocessors are the tiny "brains" inside microcomputers and hundreds of other electronic devices.

Microprocessors of the first generation were too feeble to power anything resembling a personal computer. But they were—and still are—powerful enough to drive pocket calculators and control machines performing simple tasks. They have become, like the motor, a tool for every use. Millions are sold each year to operate home burglar alarms, remote television controllers, programmers for videocassette recorders, and dozens of toys. The "4-bitter" was the hottest selling microprocessor every year until 1988, when 8-bit chips took the lead.

Microprocessor chips in a variety of sizes provide the delicate control that improves the efficiency of power plants, cars, and heating and cooling systems in buildings, which translates into lower operating costs and less pollution. They are also widely used in the cockpits of advanced commercial airliners to control navigation and other avionics systems, thereby improving the efficiency of aircraft and crew.

Second-generation microprocessors— the mighty 8-bit chips that appeared in 1974—had enough calculating power to operate low-performance computers. These "microcomputers" were built around microprocessors and remained curiosities, the electronic playthings of hobbyists, until the introduction of third-generation chips in 1975. These delivered much better performance than their forerunners and brought down microprocessor prices to as low as $25 from nearly $200. Within two years, they spawned commercial lines of home microcomputers that were soon being used for nonhome tasks.

Microprocessors make modern airliners easier to fly by displaying flight instrument data on video screens, as in the cockpit of this advanced 747. These data display screens and other design improvements helped reduce the number of cockpit lights, switches, and gauges to fewer than 400 in this aircraft compared with nearly 1,000 in earlier models.

It was, however, the fourth generation— mostly the powerful 16-bit microprocessors— that convinced the traditional computer industry that microcomputers based on these chips were powerful enough for more than home video games. And in 1981 the mainframe-computer industry began marketing microcomputers for such computational tasks as graphics, desktop publishing, managing large data bases, and computeraided design in business and industry.

Small, inexpensive personal computers built around microprocessors bring computer power into millions of homes around the world. Ready-to-use programs have made it easy for children as well as adults to use these computers for video games, word processing, and dozens of other applications.

Microcomputers would have been useless without software, the programs of simple commands that tell computers how to perform complex tasks. Each computer has coded operating instructions already wired into it, but they are awkward for people to use. So the codes have been translated into languages, such as BASIC, FORTRAN, and COBOL, based on easy-to-use words and symbols. The languages further simplify programming by using single symbols for some simple functions that are generated by a series of instructions. For example, "*" might trigger the series of instructions for the function "multiply". The languages, in turn, are used to program larger sets of instructions, or programs, that perform complex tasks such as word processing. For instance, word processing software might be programmed so that typing C-O-P-Y initiates the thousands of instructions for duplicating a page of text on the computer screen.

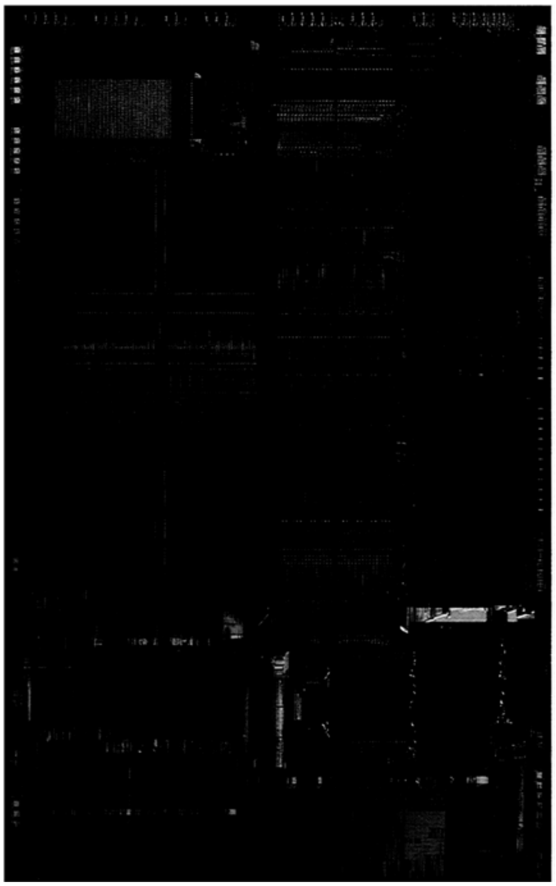
Software was not readily available for the earliest microcomputers. Hobbyists labored to compose their own operating systems —programs telling a computer how to run itself—and application programs, for tasks such as word processing or playing Space Invaders. However, a cottage industry of programmers began to sprout in the mid-1970s and was soon turning out commercial programs for a multitude of applications, including word processing, video games, inventory control, and personal finance management.

The combination of ready-made software and low-cost microcomputers produced the true personal computer, a machine so affordable and easy to use that it was available to almost everyone. The impact has been enormous. PCs have done for computing power what the printing press did for knowledge—gave it to the masses. Connected by telephone lines, PC users tap into networks of computers as well as into data banks for stock quotations, medical information, and legal cases. In the future they may be able to draw on data bases of library books, newspapers, and magazines from all over the world.

Today's microprocessors greatly outperform their 4-bit ancestors. One 32-bit chip, for example, is a thousand times faster. Another carries 500 times more transistors, packing 1 million of them onto a chip no bigger than a postage stamp. Others—made by a process called CMOS, for complementary metaloxide semiconductor—use less energy and produce less heat than conventional chips. They are used in satellites, portable computers, and other devices where energy consumption is critical. The speed of some microprocessor chips has been improved by a design known as RISC, or reduced instruction set computer, which uses a small number of simple instructions. Complex instructions, which occur infrequently, are handled in software. Larger memory chips have also been developed to hold the complex programs that exploit the power of the new microprocessors.

In the future, multipurpose microprocessor chips will probably grow to 64 bits, some containing as many as 10 million transistors. Application-specific processors will be designed for just a few specific tasks. Such chips are faster and more efficient at a single job than a chip designed to do everything. The key to making application-specific processors will be advanced computer-aided design (CAD) systems—themselves based on microprocessor chips—that design such specialized chips quickly and inexpensively.

The new microprocessors and the systems they run will have the power to generate better graphics and higher-quality three-dimensional images for CAD systems. Microcomputers, for example, will certainly be more adept at human talents, such as understanding spoken words, speaking, or even learning and reasoning—artificial intelligence. And they will be able to process incredible amounts of data at lightning speeds. Work is under way on a new generation of supercomputers, which would link hundreds, even thousands, of microprocessors in parallel arrays. Each chip would work on a different part of a massive problem, such as a global weather forecast, solving the entire problem in a fraction of the time needed if each part were solved one after the other. The challenge of parallel-array systems is to develop mathematical formulas and operating systems to coordinate the work of all the microprocessors.



The i486 microprocessor squeezes 1.18 million transistors—500 times more than the first microprocessor —onto a chip about the size of an adult's thumbnail.

An even greater challenge lies in figuring out how to take best advantage of the wonderfully powerful computers based on these new microprocessors. That is the task of the programmers, whose work is limited only by their ability to think creatively.

4

Computer-Aided Design and Manufacturing

Hidden behind factory walls throughout the world, another industrial revolution is unfolding around the computer. It is changing industry as profoundly as power machinery did in the eighteenth century and mass production, typified by the assembly line, did early this century.

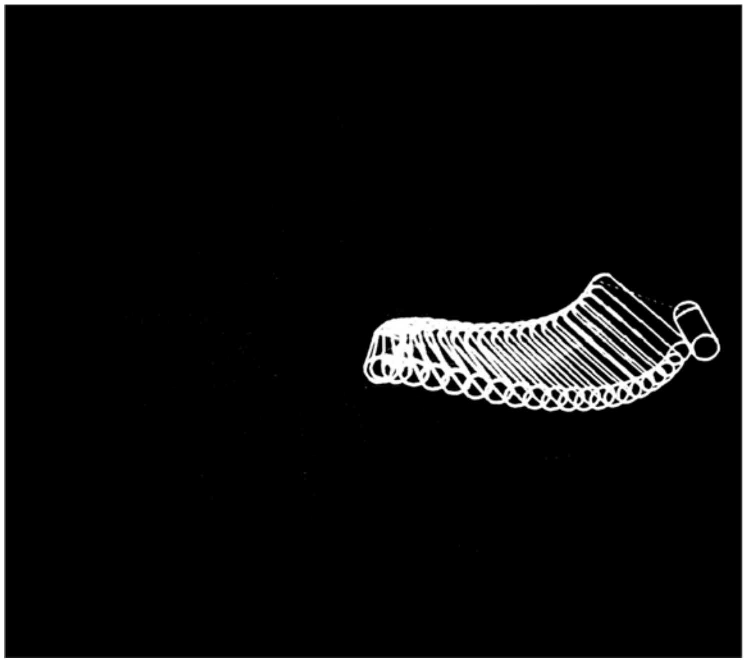
A worker sets up a computer-controlled profiling machine that cuts complex parts out of aluminum, steel, and titanium. The program of instructions for making a part is usually generated on a separate CAM system, then transferred to the machine's computer, which can store programs for dozens of parts.

Computer-aided design and computer-aided manufacturing—CAD and CAM—have already increased speed and efficiency for many manufacturers. They are improving the quality of products while decreasing the time to take them from idea to market. And they are giving manufacturers the flexibility to respond to an ever-changing market.

Essentially, CAD covers the use of computers on the design side of a product while CAM refers to their use on the manufacturing side. On the design side, engineers use computer graphics to design the new part or product. Other engineers use analytical programs to determine whether the part, as it is designed, will hold up under the stress of actual use. Drafters use computerized devices to add detail to the design and produce the final drawings. On the manufacturing side, computers help engineers write instructions for the automatic tools that will create the part. Small computers on the machines themselves allow the machines to be quickly changed from producing one part to making another. Small computers have also spread to other areas of the factory, controlling manufacturing processes, operating robots that move pieces from one machine to another, and guiding automatic carts that move materials, parts, and finished products around the plant.

Modern CAD and CAM systems began appearing on the market around 1970, following the marriage of CAD and CAM computer programs to minicomputers in the $100,000 range. Previously they were limited to a few large manufacturers of aircraft, autos, and textiles who wrote their own CAD and CAM programs and ran them on mainframe computers that often cost a million dollars or more.

The roots of CAD and CAM reach back to two Air Force programs in 1949. CAD hardware—the machines—began with efforts to build an air defense system by linking radar to computers, whose data were displayed on video screens. At the same time, the forerunner of CAM software— programs to run the hardware—began with the creation of punched tapes to operate numerically controlled (NC) machines. These machines cut, drill, and perform other tasks according to instructions fed into their control units on a punched paper tape. Tapes for the first generation of commercial NC machines were laboriously punched by hand. After the creation of a computer programming language called APT, for Automatically Programmed Tools, tapes were generated on mainframe computers.



The screen of a CAD/CAM system illustrates the complex tool path that a milling machine must follow to create the curving surface of an impeller blade for a jet engine.

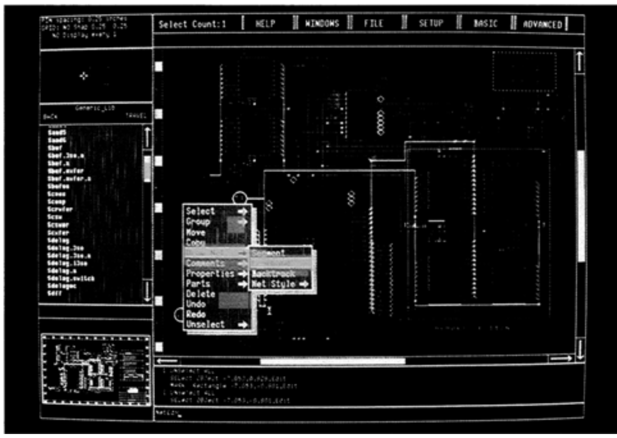
Modern CAM really began in 1969 with the appearance on the market of a less complex language, called Compact II, for programming NC machines. Before then, companies produced their NC tapes by hand, made them with APT on a mainframe computer, or sent the work to be done on a time-sharing basis on an out-of-house mainframe. Compact II was initially a time-sharing service. But later the program was sold to run on a minicomputer, further reducing the cost of the service. With such a CAM system, an engineer could quickly write a program to produce a part, press a button, and the computer would punch out the correct instructions on an NC tape. The tape was taken to the NC machine to make the part.

Today, even easier languages have been introduced for programming NC machines. In some systems, the tapes have been eliminated by hooking the programming computer directly to the machine tool. And many NC machines have small computers that store several programs for producing different parts.

Computer-aided design has sparked its own revolution within the broader movement toward factory computerization. Like the telescope and the microscope, CAD systems have opened up new worlds of understanding to the engineers who design, analyze, and test today's sophisticated products. CAD is applied to nearly every large or complex engineering project undertaken today, from designing modern jumbo jets to planning energy-efficient buildings. It was, for example, extensively used in designing *Stars & Stripes,* the racing yacht that won the America's Cup competition held in Australia in 1987. And CAD is absolutely essential for designing the tiny circuits in microprocessors and other integrated-circuit chips that run most electronic devices.

The second wave of the CAD revolution rose in 1981 with the introduction of single-user CAD workstations. Workstation computers are powered by microprocessors and generally have more computing power and graphics capability than personal computers, which are also based on microprocessors. However, a workstation costs about one-tenth as much as a minicomputer. Today, the price of some workstations is under $10,000, and their power equals that of most minis.

Modern CAD did not spring full grown into existence. It began as a drawing aid for drafters and developed along two parallel paths. One led through electronic design, and the other through mechanical design.



A microprocessor is designed with the aid of an electronic CAD system. Using this program, an engineer can quickly design an electronic circuit by placing and connecting symbols of components on the screen. The computer automatically adds the details to the final design.

An engineer uses a workstation and a mechanical CAD program to design a new wheel hub assembly.

In the electronics industry, the great problem facing engineers in the late 1960s was the design of increasingly smaller and more complex integrated circuits on tiny silicon chips. NC machines had been developed for cutting the stencil-like masks used in etching circuit patterns onto chips. But instructions for the machines were still calculated and punched into the tapes by hand. In 1970 one of the first commercial electronic CAD systems, called Design Assistant, appeared on the market. It consisted of a minicomputer, screen, sketch pad, and keyboard plus software. The engineer drew the circuit on the pad, watching the design appear on the screen. After correcting mistakes, the engineer pressed a button, and instructions for cutting the design were punched into an NC tape. This early CAD system sold for about $150,000. But just two years later, improved versions were selling for half that price.

In the mid-1970s, new electronic CAD programs for “design rule check” came to the market. They not only copied the circuit pattern but also told the engineer whether the patterns were too close together or violated any other design rules. In the early 1980s, even more intelligent programs were developed. Called “performance models,” they could tell a design engineer what would happen when electric signals flowed through the circuit and point out flaws in the design. Today, no self-respecting engineer would design a circuit without performance modeling.

One of the first modern CAD systems for mechanical design arrived in 1971 on the heels of electronic CAD. It was really a drafting aid that consisted of a drawing table, computer, screen, and plotting arm that digitized its movements: that is, translated them into digital electronic signals. By moving the plotter to different points on the table and telling the computer what to draw between them, a draftsman could copy a design into the computer while watching it materialize on the screen. After correcting the design, the draftsman pressed a button, and the plotting arm automatically redrew the design on a clean piece of paper. Called Interact I, this mechanical CAD system ran on a minicomputer with four terminals and cost around $375,000.

The early mechanical CAD systems could draw points, lines, circles, arcs, and symbols in two dimensions but with no mathematical idea of what they were doing. By 1973 more intelligent programs were developed that could not only create three-dimensional figures on the computer screen but understood the geometry and mathematics associated with them. These were wireframe models like the 3-D figures engineers traditionally drew.

More important than creating 3-D design models, though, was the intelligence of such a CAD program. Using a mathematical model of the design in its data base, it could answer questions from the engineer: How long is that line? What is the area of this plane? Where is the center of gravity? And if, for example, the engineer tried to put a 2-inch piece in a space 1.75 inches wide, the CAD program would reply that the piece was 0.25 inch too long. It was smart enough to calculate and draw a new line through a model if the engineer so requested. It could also calculate a section, in effect slicing the model in two so the engineer could see how parts fit together inside the design. And it could turn the model to be viewed from different angles. This was not just a drafting device but a true CAD system that helped an engineer design a part.

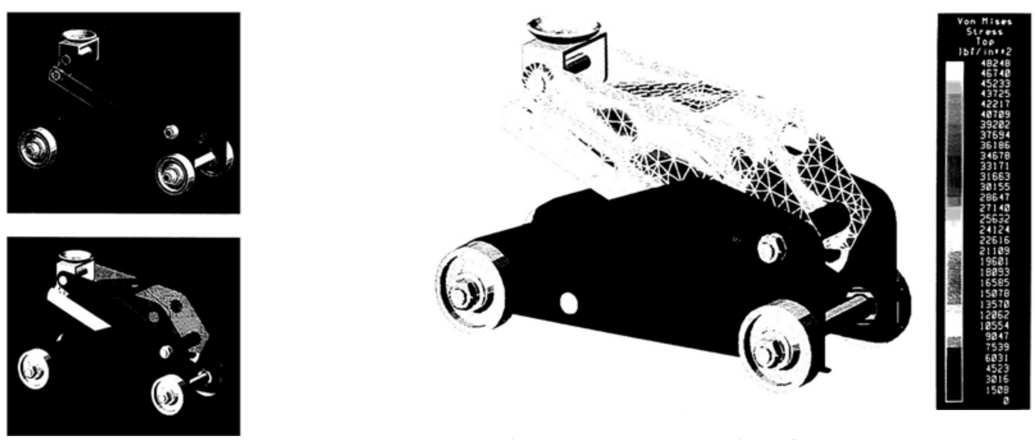
The newer mechanical CAD programs were also intelligent enough to perform simple analyses on the design, to see how it would hold up under the stress of actual use. They could also prepare a design for more complex analysis by dividing the model into the hundreds or thousands of geometrical shapes that formed it. The data were then sent to analytical engineers who tested the design on powerful mainframe computers. This preparation, which the CAD program did in seconds, would have taken engineers hundreds of hours to do by hand.

In the late 1970s, computer models of solid objects came onto the market. These were even better for analysis than 3-D wireframe models. Nevertheless, since there are so many variables in designing a mechanical part, mechanical CAD systems today are only beginning to reach the level of performance modeling that electronic CAD systems achieved nearly a decade ago. However, programs are being developed that allow engineers to analyze mechanical systems for a large number of variables. For example, engineers soon could be able to model the performance of a mechanical system as complex as a commercial power plant.

CAD programs of the late 1970s also began linking to CAM systems on the manufacturing side of factories, eliminating the need for many paper design drawings and reducing the time manufacturing engineers need to write instruction programs for the NC machines that make the parts. Previously, engineers had to study the paper drawings in order to calculate tool movements. These CAD systems, however, could simulate the movement of a cutting tool around the design model in order to determine the necessary tool movements. These were not only determined more quickly using CAD models, they were also more accurate.

In the future, engineers will seek ways to use CAD and CAM more effectively. Today CAD programs are linked to CAM systems in only a small number of factories. On the design side of factories, separate CAD systems often exist independently in design, drafting, and engineering departments. Drawings are still often carried from one office to another, where it may take 50 to 100 hours to enter the data into another computer system. On the manufacturing side, computers are only slowly being applied to tasks that they could perform faster and more effectively. In addition, many factories could greatly increase their productivity by joining isolated computerized systems into integrated networks. Such computer-integrated manufacturing, or CIM, has begun in a few factories, and some of the results have been spectacular. For example, the highly integrated use of computerized systems at one company that manufactures motor-starter components helps it produce and ship the parts in less than 24 hours, a job that used to take about 15 days.

Another challenge in computerizing the manufacturing process lies in integrating computers throughout the company, not just at an individual factory. Such a CIM network might include finance, market forecasting, material ordering, customer service, and stocking, as well as CAD and CAM. Current debate swirls around how to integrate the computers—whether to design one big network or to integrate computers only where and when it becomes necessary. Too much integration could flood and slow the network with needless data.



An engineer uses a mechanical CAD program to analyze stress on the lifting arm in the design of an automobile jack assembly. The program creates a solid model of the device, top. It uses a mesh to divide the lifting arm into small "finite elements" that are analyzed for stress individually, center. The program then uses color coding to indicate varying levels of stress throughout the component, telling the engineer where to strengthen the design, bottom.

Computers have found an indispensable role to play in manufacturing through CAD, CAM, and other automated systems. No one really disagrees. How big a role they will play, and when, are the real questions for the future.

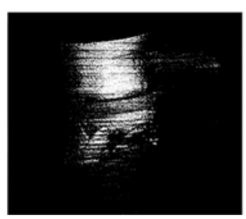
5

CAT Scan

Ever since 1895, when German physicist Konrad Roentgen took the first roentgenogram, x-ray pictures have been clouded by shadows of bones, teeth, and tissue piled together on one piece of film. But the marriage of modern computers to this old technology has given birth to a machine that produces clear, detailed images of things inside the body.

Right: A patient lies quietly as a CAT scan's x-ray tube shoots from hundreds of points around her head. Sensors opposite the tube record the strength of beams passing through the patient. With this data. the CAT scan computer generates an image showing the structure in that cross section of her head.

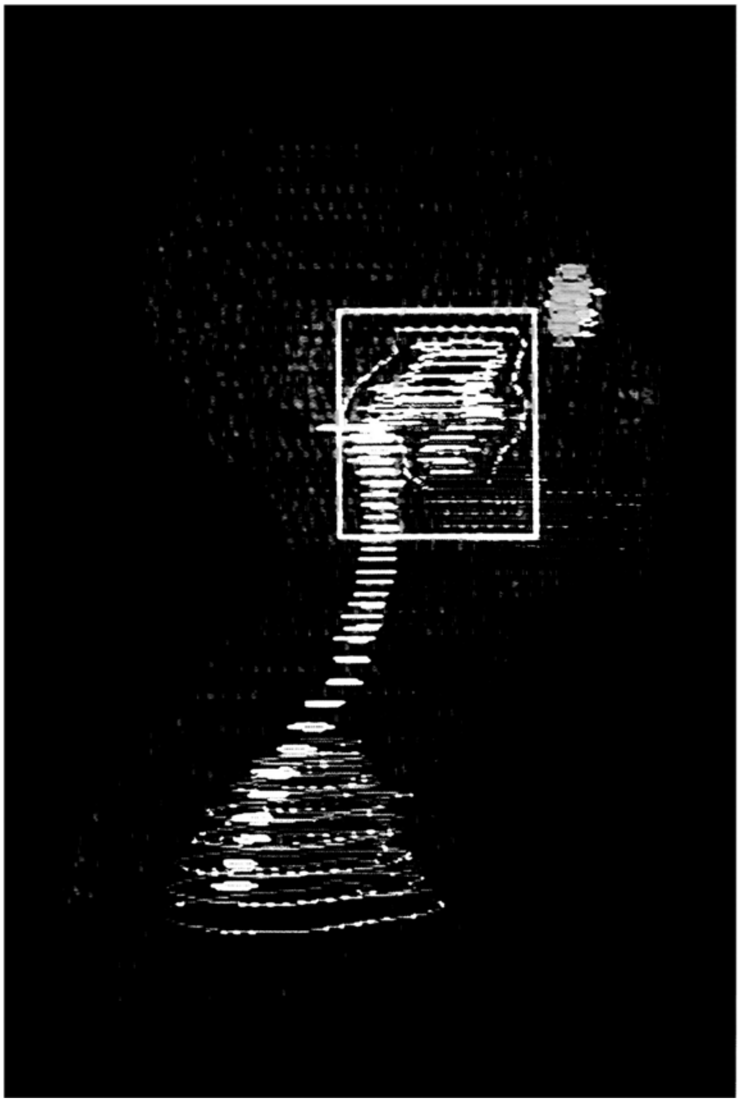
The machine is called a CAT scan, for computerized axial tomography scanner. The wedding of computers to other diagnostic techniques has subsequently led to ultrasound imaging, magnetic resonance imaging (MRI), and other new procedures that peer inside the body without resorting to surgery. Indeed, many doctors believe that more progress has been made in medical diagnostics since the CAT scan was introduced than in all previous medical history.



A young man's vertebrae, broken in a motorcycle accident, appear almost lifelike in a three-dimensional image created from dozens of CAT scans. CAT scans are particularly good for showing the fine detail of bone structure.

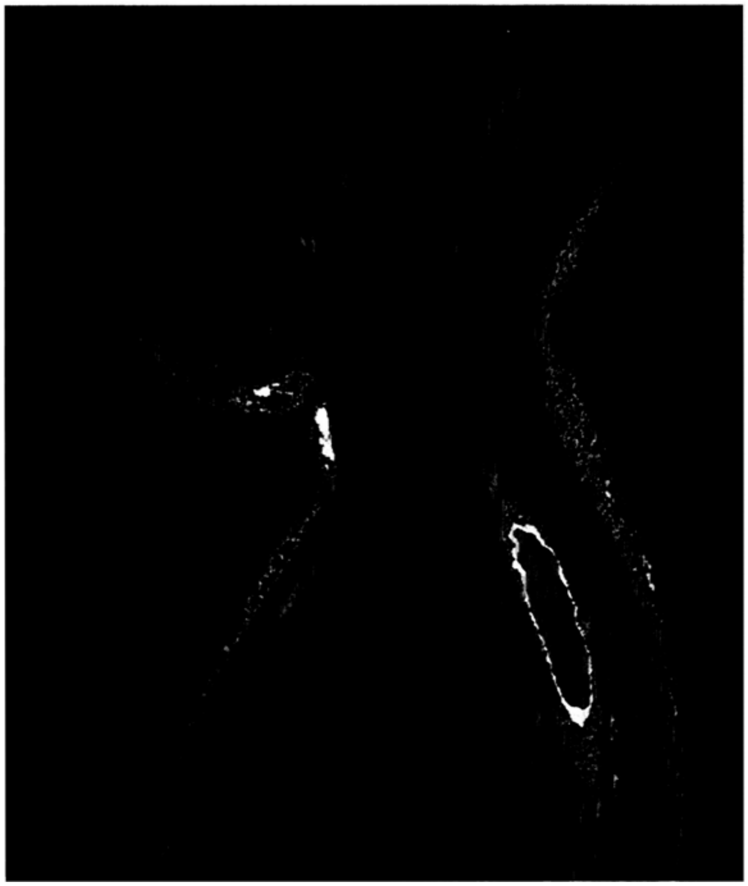
CAT has so far had the widest impact of the new imaging technologies. It has saved untold numbers of lives by quickly finding tumors, infections, bleeding, and blood clots that would have been found too late or missed altogether by regular x-rays or other diagnostic techniques. A normal series of 30 scans is performed in about 20 minutes and usually without injections. CAT scans have reduced the need for some diagnostic techniques that require uncomfortable injections and a stay in the hospital.

The procedure has also revealed to researchers brain abnormalities in some persons suffering from schizophrenia, alcoholism, manic-depressive illness, and Alzheimer's disease. CAT scans locate brain tumors precisely for radiation treatment and are used to build three-dimensional models for reconstructive surgery. CAT is especially good at finding internal injuries because it easily distinguishes between blood and tissue. Some hospitals now have a CAT scanner in the emergency room, and the U.S. Army is developing a rugged, lightweight one that can be transported by truck or helicopter to medical stations in combat zones.



A cross on this three-dimensional image generated from a series of CAT scans marks the location of a tumor near the center of the patient's head. Color coding shows sensitive areas, such as the eyes, spinal cord, and lungs, that should be protected from unnecessary radiation when the tumor is treated.

CAT—often shortened to CT, for computed tomography—doesn't make a flat picture on photographic film, like a normal x-ray. Instead, it constructs a television image based on density measurements of a “slice” of the patient. The process is something like seeing a slice of salami without cutting the meat.



An enhanced MRI scan shows a tumor growing in the spinal cord of a 4-year-old girl, who lost her ability to walk. A doctor quickly removed the tumor, and the girl eventually recovered the use of her legs.

To measure density, the CAT scan's x-ray tube shoots a thin beam edge-to-edge through a slice while circling the patient. Detectors circling opposite the tube measure the strength of the emerging beam—and therefore the density of the slice—from hundreds of points around the patient. With this information, the CAT scan computer calculates the density for each of more than 250,000 tiny bits of tissue in the slice. It then displays these values in a television picture showing density patterns that reveal the fine structure of the slice.

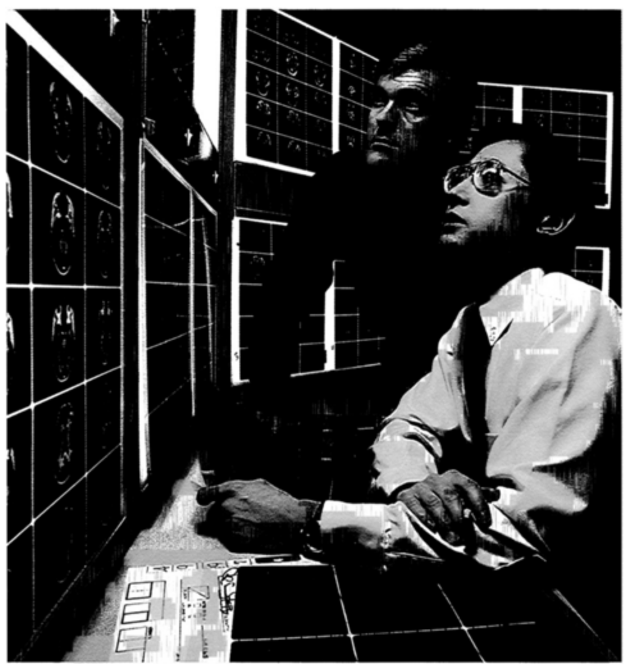
The practical CAT scanner emerged from the confluence of several new technologies. The most important developments were low-cost minicomputers and, later, parallel-array computers that could perform many calculations at the same time. These high-speed computers and the mathematically complex programs to operate them made it possible to run millions of calculations for each slice. In 1979 the Nobel Prize in physiology or medicine was awarded to British research engineer Godfrey Hounsfield for pioneering the CAT scan and to U.S. physicist Allan Cormack for work on the mathematics behind it. The first CAT scanners were installed in Great Britain in 1971 and in the United States two years later. Today they are used in more than half of U.S. hospitals and in hundreds of clinics.

Very small x-ray detectors and ultrasensitive signal amplifiers have greatly increased the speed of CAT scanning. An early scan took about 4 1/2 minutes. Today it takes less than 2 seconds as a scanner's 1,000 detectors each record 2,000 separate measurements. The machine's sensitivity has improved, too. Now, for example, CAT can detect a liver tumor of almost the same density as normal tissue. The difference would not show up on a regular x-ray. Tomorrow's scanner will produce even more detailed images as scan slices become progressively thinner and scan times decrease even more. The patient will move continuously through the scanner, like a car on an assembly line, completing a 40-slice series in about a minute. And it may soon become routine for a treating doctor to beam the scan image via satellite to a consulting specialist thousands of miles away.

Small, powerful computers have been applied to other diagnostic imaging techniques since the CAT scan. Each uses a different means of probing the patient, but the image is constructed by computer. Low-level radioactive isotopes are injected into the blood during positron emission tomography (PET) and single-photon emission computed tomography (SPECT). With digital subtraction angiography (DSA), a computer subtracts an earlier x-ray image from another one taken after a contrast substance has been injected into the blood, leaving the clear contrast outline of blood vessels on the second image. Ultrasound devices bounce high-frequency sound waves off internal surfaces to indicate their position and motion.

The most promising computer-assisted technique, though, uses magnetic fields and radio waves to coax information from the nuclei of atoms in body chemicals. This nuclear magnetic resonance imaging, or MRI, is particularly good for examining the brain and spinal cord, whose surrounding bone is invisible to it.

CAT culminates the development of Roentgen's technology. And although traditional x-ray pictures still account for 80 percent of medical diagnostic imaging, they may one day be completely replaced by computer-generated video images. The continued development of CAT, ultrasound imaging, and especially MRI should further reduce the need for exploratory surgery or invasive imaging techniques such as those involving injection of contrast agents that may occasionally cause allergic reactions. In fact, in 10 or 15 years, MRI may be able to perform an entire diagnostic chemical analysis of a patient, without breaking the skin.



Doctors discuss features revealed by MRI images. MRI employs radio waves and magnetic fields to produce images in which bones are invisible. It is therefore very useful for looking at soft tissue inside the skull and spinal column.

Advanced Composite Materials

The unusual design of the Starship business plane— slender wings, vertical wing tips, down-hanging rudder, and winglets on the nose— masks the real revolution behind this aircraft. Its body and wings are made entirely of advanced composite materials far lighter and stronger than the aluminum most aircraft are made of today. As a result, the plane needs less maintenance than conventional aircraft and flies as far on a gallon of fuel as planes much smaller.

Right: A strong, ultralight leg prosthesis of graphite/epoxy composite helps an athlete compete in world-class bicycle races.

Advanced composites like those in the Starship were unheard of 25 years ago. Yet they have already spread throughout the transportation industry and into everyday objects where higher performance provides an advantage. They add lightness and strength to racing boats and cars, golf clubs, and electric guitars.

Composites are simply a matrix of one material reinforced by fibers or particles of another. Humans have been making composites since the ancients discovered that putting straw into mud bricks makes the bricks stronger. Today steel rods are used to reinforce concrete highways, bridges, and buildings. Resin reinforced by glass fibres is probably the most widely used composite today.

Advanced composites, however, are in a class alone. Most were originally developed to provide lighter, stronger, more temperature-resistant materials for military aircraft and spacecraft. Skyrocketing fuel prices in the 1970s made the new materials attractive to civil aviation, where their lower weight has helped cut the cost of operating airliners. The broadening market and more efficient processing techniques have reduced the cost of composites to a level where they can now be used in many other products, especially sporting goods.

Graphite/epoxy and other advanced composite materials are used to construct the entire body and wings of the Starship business plane and account for more than 70 percent of its overall structural weight.

The matrix of an advanced composite is often an organic material, such as epoxy resin, but can also be metal or ceramic. High-strength fibers, such as graphite or Kevlar, are frequently used as reinforcements. But many combinations of matrix and reinforcement are created for particular uses. Knowledge about their interactions—how fibers or particles function within a matrix—is the key to designing these high-performance materials. And it has ushered in an era of designing new materials to meet new needs.

Advanced composites came directly out of Air Force efforts in the early 1960s to find materials with higher strength-to-weight and stiffness-to-weight ratios than aluminum. The most promising was boron, which is stronger than steel but weighs less than aluminum. The challenge, however, was to put it into a usable form. The best, easiest, most cost-effective method turned out to be making it into a fiber that could be embedded in a matrix of epoxy. Epoxy holds the fibers in place, distributes the load among them, and protects them from the environment. To make an aircraft part, strips of epoxy tape with fibers running through it are laid in a mold in directions that will reinforce sections where strength is critical. High heat and pressure transform the epoxy into a solid, lightweight part. Such composites were introduced to operational aircraft in tail sections of the F-14, which was delivered to the Navy in 1972.

Layers of woven Kevlar fibers strengthen composite downhill snow skis while reducing weight and damping vibration. Advanced composite materials are used in many sporting goods, whose high performance provides a competitive advantage.

Boron fiber is expensive. So parallel work in England and Japan focused on graphite as a less expensive high-strength fiber. Graphite is a form of carbon, and its fibers are made by transforming organic fibers such as rayon, acrylic, or pitch.

The first high-strength graphite fibers produced in the late 1960s were made by a time-consuming, labor-intensive process and cost around $400 per pound. It began with an acrylic fiber that was wound on steel racks to stretch the fiber and align its long molecules into stronger, parallel orientation. The fiber was heated at low temperature to stabilize the orientation, then cut into strands and slowly baked in a furnace with inert gas—usually nitrogen—to burn away impurities. The remaining graphite fibers were treated with chemicals to help them bond to a resin matrix.

In 1971 a U.S. company started making graphite fibers by a continuous process that took less than eight hours. These fibers cost only $125 per pound, and their price dropped steadily over the next decade. The first production graphite-composite parts went into F-15 aircraft delivered to the Air Force in 1974. And today's Starship business plane is made primarily of graphite/epoxy.

The first commercial graphite-composite products, though, were sporting goods. In 1972 a California company began making golf club shafts of graphite/epoxy, which is stronger and lighter than the steel in conventional shafts. The new shafts appeared in Japanese golf clubs the following year. Graphite composite increased stiffness and reduced shaft weight by about 40 percent, allowing golfers to swing the club faster and drive the ball farther than they could with heavier clubs. Composite tennis rackets appeared next, followed by fishing rods, race-car chassis, and other sports equipment.

Auto manufacturers are investigating graphite composite to replace steel in passenger cars, but its price is still generally too high to make it economical for mass-produced vehicles. However, since 1988 a graphite composite has been used to reinforce aluminum drive shafts on some light trucks.

Another high-strength fiber, Kevlar, is widely used in composites where high tensile strength—resistance to being pulled apart—is important but the stiffness of graphite fibers is unnecessary. Kevlar is a trade name for an aromatic polyamide, or P-aramid, fiber that is derived from petroleum. It is lighter than fiberglass but five times stronger than steel on a pound-for-pound basis. It appeared commercially as a replacement for steel cord in radial tires in 1972. A high-strength form of Kevlar is used in resin-matrix composites for aircraft bodies, sailboat hulls, snow skis, and artificial limbs.

P-aramid fibers were discovered in 1965, but the breakthrough came five years later in learning how best to convert the substance into much stronger fibers. P-aramid would not melt like other plastics nor would it dissolve easily in any normal solvent used in making synthetic fibers. The substance, it turned out, needs an especially strong solvent—100 percent sulfuric acid—to dissolve it. Normal sulfuric acid solvent contains about 3.5 percent water, but this is enough to keep P-aramid from dissolving in it.

In addition, P-aramid molecules would not align themselves in strong, parallel orientation during a normal fiber-producing process. Usually a solution containing a fiber substance is forced through a plate, called a spinneret, with hundreds of tiny holes. The emerging fibers are pulled directly into a bath that leaches out the solvent, then stretched to align the molecules before being wound around a spindle. This did not work with P-aramid. The problem was solved, however, by stretching the fibers—and aligning their molecules—in an air gap just as they emerge from the spinneret. Then they are pulled into a cold-water bath that leaches out sulfuric acid, gels the fibers, and fixes molecular orientation. Finally the fibers are dried and wound onto a spindle.

High-strength fibers and particles are also embedded in metal matrices for use at high temperatures that would melt organic matrices such as epoxy. Metal-matrix composites, however, have a rather slim range of current applications in diesel and jet engines, spacecraft structures, and high-performance sports equipment.

The first commercial use of a metal-matrix composite was in high-performance diesel engines by a Japanese automaker in 1982. The composite, made of aluminum with various reinforcements, forms a reinforcing ring around the crown of the pistons. It resists wear as well as steel but is much lighter. Many automakers are investigating metal-matrix composites for use in pistons and other moving engine parts. Lightweight composite parts would use less energy and would reduce the total weight of the engine.

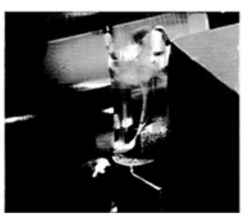
The first actual use of a metal-matrix composite, though, was probably the boron/aluminum structural tubing used in the space shuttle, which first orbited the earth in 1981. Aluminum-oxide/aluminum is now being used in handlebars of lightweight racing bicycles. And although silicon-carbide/aluminum is relatively expensive, it still costs less than half as much as the beryllium it is replacing in an instrument housing for the inertial navigation system of a Navy ballistic missile.

Composites with ceramic matrices are theoretically superior to metal-matrix composites for high-temperature applications. Ceramics—materials that are neither metallic nor organic—also have great strength and light weight, but brittleness often limits their use. Reinforcements, however, can toughen them. Since the mid-1980s, aluminum oxide reinforced with silicon-carbide whiskers has been used in cutting tools. Similar composites are being developed as armor to protect helicopters, armored personnel carriers, tanks, soldiers, and police. These composites are up to five times tougher than unreinforced ceramics, lighter than steel, and less expensive than other advanced materials now used for armor.

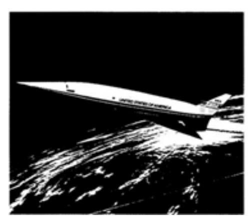
Ceramic composites are also being studied for use in car and jet engines, where their light weight and heat resistance would substantially boost fuel economy. They may find wider use in low-temperature applications where their ability to withstand hostile environments gives them an advantage over other materials. For example, ceramic-matrix composites might be used in valves and reactor vessels handling corrosive chemicals or in structures, such as satellites, that must endure the harshness of space.

Carbon is similar to a ceramic, and composites made of graphite fibers embedded in a matrix of graphite are extremely heat resistant. This carbon/carbon composite is used in the nose and leading edges of the space shuttle to protect against the searing heat of atmospheric reentry. And, because of its light weight and durability, it is being used increasingly for wheel brake linings in military and commercial aircraft.

Special composite materials are being developed for the experimental National Aero-Space Plane, which is designed to take off and land on runways, cruise at hypersonic speeds of Mach 6 (six times the speed of sound) or greater in the upper atmosphere, and reach Mach 25 while climbing into orbit. The plane's skin, frame, and engines will need to be extremely light, strong, and heat resistant. The skin, in particular, will have to withstand repeated exposure to extreme heat and cold and must be far thinner than the composite tiles that protect the space shuttle. The plane is scheduled to fly in the late 1990s. But before it does, a new generation of advanced composites will have to be born.



A strong, light ceramiccomposite tool cuts a thin chip from a fast-turning bar of tough nickel alloy. The durability of this ceramic composite at high temperatures allows it to withstand the heat produced in high-speed cutting.



The National Aero-Space Plane flies far above the earth in an artist's drawing. New advanced composite materials are being developed for its skin, engines, and other components that will allow the space plane to climb into orbit or cruise in the atmosphere at more than six times the speed of sound.

Jumbo Jet

People react much the same when a jumbo jet lumbers up to the boarding gate: eyes widen, jaws slowly drop, and speech fails until the looming giant rolls to a stop just outside the window.

The introduction of jumbo jets in the early 1970s helped relieve air traffic congestion at airports.

To most passengers, a jumbo jet is huge outside, spacious inside, and a lot more comfortable to fly than lesser planes. To the airline industry, the jumbos, with their huge capacities of 300 to 450 passengers or more, are economy of scale. It is more economical, for example, for an airline to fly 400 passengers in a single jumbo jet than 100 each in four smaller planes. Jumbos also carry passengers much farther without costly refueling stops. Earlier jets with a range of about 4,500 miles, for example, had to refuel in Hawaii during a flight to Tokyo from San Francisco. Some of today's jumbos, flying 6,500 miles or more nonstop, make the same trip uninterrupted from San Francisco, Chicago, or even New York.

Jumbo jets also help relieve air traffic congestion at airports, which can handle only a limited number of takeoffs and landings per hour whether the plane holds 4 or 400 passengers. In the mid-1960s, when the first jumbo jets were designed, air travel was growing at a rate that would double the number of passengers every five years. But the introduction of jumbos in the early 1970s reduced the immediate need to expand many airports or build new ones. In fact, no major U.S. airport has been built since 1974.

The 747, DC-10, and L-1011 jumbo jets joined the commercial air fleet in 1970, 1971, and 1972, respectively, forming a necessary link in a chain of events that introduced long-distance air travel to the masses. Since then the combination of rising fuel prices, lower air fares, and economical long-range jumbos has helped triple the annual revenue passenger miles (one RPM equals one paying passenger carried one mile) logged by the U.S. airline industry. In 1988, 420 billion RPMs were logged, and the figure is projected to surpass 760 billion by the year 2000.

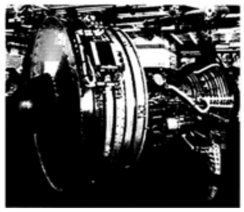
The origin of the jumbo jet lies in the competition for the giant Air Force C-5A cargo plane, which began operational flights in 1969. The challenge of building the jumbos was to fit those design advances plus other state-of-the-art technologies into a huge machine that was not only safer than earlier airplanes but less expensive to operate. The 747, for instance, reduced the per-mile cost of carrying a passenger 20 to 30 percent.

The jumbos also introduced an era of safer aircraft designed with a strong emphasis on several redundant, or backup, systems. The failure of a single system would not cripple the airplane. For instance, designers of the 747 put four main landing-gear legs on the plane instead of the usual two and added a middle spar to the wings. If the front spar were damaged in a collision, the middle and rear ones could hold the wing together for landing. Designers of the L-1011 built in four separate hydraulic systems to operate the critical pitch control system—elevators and stabilizers—which moves the nose up or down. Three are powered by the plane's three engines and the fourth by an auxiliary power unit. The DC-10 was designed with five generators—each of which can keep the plane flying—plus an emergency backup battery system. Three of the generators are powered by the aircraft's three engines, one by an auxiliary power unit, and the other by an extendable windmill.

The size of jumbo jets sets them apart from earlier airliners, and so does their increased emphasis on safety. The four main landing-gear legs on the 747 instead of the usual two are an example of the multiple backup systems that add a wide margin of safety to jumbo jets.

The jumbo jets owe much of their success to the high-bypass engine, which was introduced to military aviation on the C-5A and to the commercial sector on the 747. They help the big planes fly farther, consume less fuel per passenger mile, and climb into the sky with a murmur compared with the scream of earlier jet aircraft. Advanced metal alloys, new cooling systems, and the high-bypass design help the engines deliver almost twice the thrust per pound of engine weight, while using 20 to 25 percent less fuel per pound of thrust than conventional turbojet engines.

The core of a high-bypass engine operates like a pure turbojet, in which whirling compressor blades pull air into the engine's combustion chamber, where the air and fuel are burned. This creates a hot, rapidly expanding gas that thrusts the engine



The high-bypass engine gets its name from the huge fan that thrusts air past the combustion chamber, the section where the technician is working. In the conical back end of the engine, expanding gas from the combustion chamber spins turbines on a shaft that turns the fan.

Large fans on the high-bypass engines of these DC-10s push air out the back of the silver engine cowlings while combustion chambers shoot expanding gas through the gray cones.

forward. The gas also spins a turbine, whose shaft runs back through the hollow engine core to turn the compressor blades.

The high-bypass engine, however, takes advantage of the fact that for a given power level, a large volume of slowly moving air will generate more thrust than a small volume of fast moving air. In the high-bypass engine, the turbine also turns a wide fan at the front, which pushes a large mass of air past the combustion chamber. The ratio of air bypassing the combustion chamber to air flowing through it was 5:1 on the first commercial high-bypass engines and 8:1 on military versions. The fat cowling covering the large fan clearly distinguishes the high-bypass engine from the slender, less efficient turbojet.

The new engines are much quieter, too. All the thrust of a turbojet comes from its exhaust, which shoots out at twice the speed of sound with an ear-splitting roar. But a high-bypass engine mixes quieter low-velocity air with the high-velocity exhaust to slow its speed and reduce its noise. The noise level of the first DC-10's, for example, was about half that of earlier four-engine airliners.

High-bypass engines are also more efficient than earlier turbojets in part because they operate at higher combustion temperatures. Turbines in the new engines tolerate burner-exit gas temperatures up to 2,800 degrees F, about 500 degrees greater than the earlier engines. Much of this higher tolerance results from new air cooling systems that allow turbine blades to operate in gas streams at temperatures higher than their material melting point. The blades are cooled by compressed air that is channeled around the combustion chamber and directed onto the whirling disk holding the blades. A pressure differential causes the air to flow into the base of each hollow blade, where a network of passages carries the air throughout the blade to cool it from inside. As air escapes through strategically spaced holes, it flows over the external surface in a protective film that insulates the blade from hot gas. Gas temperatures are 200 or more degrees hotter than the melting point of the blades.

Some of the increased engine performance also came from an advanced process, called directional solidification, for casting the nickel-alloy turbine blades. Whirling blades under high centrifugal force tend to creep, or elongate, at turbine operating temperatures. Creep causes cracking along the boundaries between alloy crystals, which form when the blade is cast. In earlier blades, the crystals solidified in random alignments.

Directional solidification, however, forces the alloy to solidify in long crystals that grow from one end of the blade to the other. This eliminates crystal boundaries across the blade and so reduces creep and cracking. Directional solidification begins by pouring molten alloy into a mold that sits inside a hot furnace. At the bottom of the mold is a water-cooled chill plate, where the alloy starts cooling and crystals begin forming. The mold is slowly lowered out of the furnace, causing the first crystals to continue growing up in parallel columns toward the top of the mold. Turbine blades made this way could operate at temperatures up to 100 degrees F hotter than conventional blades.

Right: Nickel-alloy turbine blades cast as single crystals have greater strength and durability and higher temperature capability than blades made of earlier materials. The wavelike patterns, enhanced for this photo by chemical processing, are caused by minute chemical differences between parts of the crystal that solidify earlier in the casting process and those that solidify later.

The heat tolerance of turbine blades has since been raised another 100 degrees by making each blade out of just one crystal. With a single crystal and no boundaries, engineers could remove from the alloy several boundary-strengthening ingredients that, essentially, had prevented the blades from tolerating higher heat. The trick was to select a single crystal that would grow both vertically and horizontally to fill the entire mold. The problem was solved by putting a corkscrew bottleneck between the chill plate and the mold. As with directional solidification, several crystals start to grow from the chill plate. But the bottleneck is small enough that only the crystal with the best horizontal and vertical growth properties can worm through the corkscrew into the mold. The first single-crystal turbine blades went into engines for the midsize 767 jetliner in 1982 and subsequently into new jumbo-jet engines.

L-1011s, here under construction, have four separate hydraulic systems for added safety. They operate the elevators and stabilizers on the wings, which control the pitch of the jumbo's nose.

Many of the engineering advances developed for jumbo jets have been incorporated in smaller aircraft. High-bypass engines are now found on nearly all new commercial airliners of every size. The jumbos, in turn, are benefiting from new technologies developed for commercial aircraft in general: composite structural materials, automated landing and flight systems, and “all glass” cockpits in which instrument readings are displayed on color television monitors.

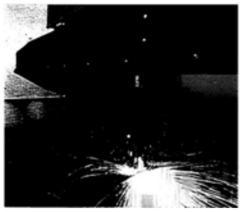
Over the next 10 to 15 years, the current family of jumbos will continue to expand in size, range, and capability. Future jumbos may weigh 1 million pounds, compared with 870,000 pounds today. They will carry over 600 passengers more than 8,000 miles nonstop. Currently, only short-range jumbos carry that many passengers and long-range jumbos carry many fewer. In addition, the three jumbo families will be joined by a fourth, the A330/340, in the early 1990s.

Supersonic transports, such as the Concorde, generate an unacceptable sonic boom that limits their use over populated areas. The next really advanced commercial aircraft therefore may be one that travels at hypersonic speeds at and above Mach 6 (six times the speed of sound). A proposed hypersonic plane, the National Aero-Space Plane, is expected to travel at speeds and altitudes where its sonic boom would create less of a problem. It will probably burn liquid hydrogen in a propulsion system that uses jet engines while in the atmosphere and rockets while in space. It remains to be seen, though, whether hypersonic planes will become economical for long-haul commercial transport. In the meantime, the jumbos and their descendants will undoubtedly remain the workhorses of the airlines into the twenty-first century.

8

Lasers

Before lasers were invented, scientists dreamed of harnessing the unique properties of light to study the swift motion of molecules, atoms, and electrons. The military wanted light's awesome power to annihilate enemy tanks, planes, and missiles. Once the practical laser was built, however, the "glamorous blowtorch" began doing jobs no one had dreamed of. Today lasers play music, read price tags, carry phone calls, cut cloth, perform surgery, and test the quality of air. And although the military is still waiting for a light-ray weapon, lasers have become standard research tools for scientists and engineers in laboratories around the world.



A carbon dioxide (CO2) laser cuts heavy-duty circular saw blades from 1/4-inch steel sheet. The powerful CO2 laser, the workhorse of industry, has been applied to a wide assortment of tasks, ranging from tough metal work to delicate surgery.

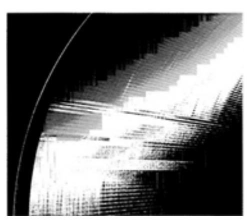
The word *laser* stands for *l*ight *a*mplification by stimulated *e*mission of *r*adiation, and laser light is unlike any other. Light waves from a laser all have the same frequency, creating a beam with one characteristic color. The light is also coherent, its waves traveling in phase—crest next to crest, trough next to trough. Coherency intensifies the waves' combined power, much as football fans intensify their combined sound by chanting in unison. In addition, the waves are almost perfectly parallel and so travel in nearly the same direction. This directionality keeps the waves concentrated in a narrow beam that widens only gradually over great distance. Incoherent light waves from the sun, light bulbs, and other nonlaser sources travel out of phase at different frequencies in a beam that quickly spreads and disappears from sight.

Laser waves are no more powerful than waves of other light. But, because of their unique properties, they are easily focused to a point that can vaporize diamond and steel. Where continuous power of this magnitude is needed, the carbon dioxide laser has been the workhorse since it was introduced commercially in 1967. It drills holes in hard ceramics, cuts through composite materials, and heat-treats metals to harden them. A CO_2 laser beam focuses to a fine point for the delicate work of cutting cloth or drilling holes in rubber baby-bottle nipples. Doctors use the CO_2 laser as a surgical knife; the laser cauterizes blood vessels as it cuts, eliminating much bleeding. Because light from a CO_2 laser is infrared and thus invisible, a red, low-energy helium-neon laser is often used to aim it.

Laser light is useful, too, in other areas of medicine. Its single-frequency nature lets a laser zap one kind of tissue while causing little harm to another. This is because some materials absorb more light energy at one particular frequency than at others. The colorless central portion of the eye, for example, absorbs little of the argon laser's green light, which is readily absorbed by blood-containing tissue at the back of the eye. Doctors, therefore, use the low-powered argon laser to spot weld detached retinas and seal the leaking blood vessels that often blind diabetics. Lasers also vaporize brain tumors, perform delicate inner-ear surgery, and remove warts and gynecological cysts. Laser light goes inside the body through fiber-optic endoscopes to burn fatty deposits out of clogged arteries, pulverize kidney stones, stanch bleeding stomach ulcers, and open blocked fallopian tubes.

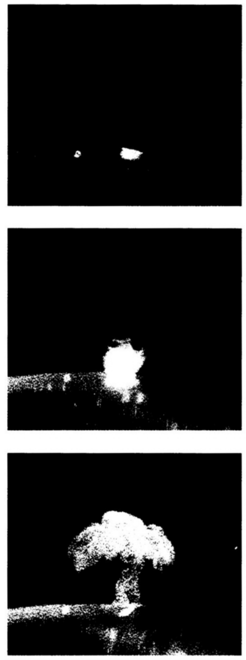
A researcher aims the beam from a YAG (yttrium-aluminum garnet) laser at a sample of gallium arsenide in an experiment to measure impurities in the semiconducting material.

Coherent light is necessary for constructing the three-dimensional pictures called holograms. They are made by shining one part of a laser beam directly onto photographic film while bouncing the other part off an object and then onto the film. Waves from the two beams interfere with each other in complex patterns that are recorded on the film. When the film is developed, these patterns act like a complex system of microscopic mirrors. They reflect back the object's image if the original laser light is shined on the film at the original angle. The patterns are so intricate that they reflect a slightly different image in slightly different directions. This lets you see the object from different angles and gives the image its three-dimensional quality.



Rows of microscopic bumps on this video disc carry digital information that is read by a laser and translated by computer into visual images.

Holograms are difficult to counterfeit and so are used as tamper-proof seals on boxes of videocassettes and auto parts as well as on credit cards and passports. Double-exposure holograms are used widely for quality control in, for example, the aircraft tire industry. Disruptions in the delicate wave pattern on a double exposure of a tire reveal defective bulges only 6 millionths of an inch high. Since 1980 holograms have been used to direct the beam in many laser scanners that read price bar codes at checkout counters. Holograms on a whirling disc bend a red helium-neon laser beam in different directions, allowing it to scan for the bar code up to 1,800 times per second. The light pattern reflecting back to



sensors from any successful scan will transmit the code.

A fraction of a second after the flash of an ultraviolet laser beam, a “smoke” plume erupts from the corneal surface of the eye, shoots upward, and turns into a microscopic mushroom cloud during a surgery experiment. Laser beams of other frequencies pass harmlessly through the cornea to perform surgery inside the eye.

The directionality of laser light makes it very useful for aligning new buildings, tunnels, and pipes as well as leveling and grading land. And the ability to switch them rapidly on and off lets lasers produce the tiny pulses needed for timing measurements of long distances. Lasers can generate pulses of less than 0.1 billionth of a second—far shorter than those made by mechanical or electrical switches. By timing pulses bounced off reflectors placed on the moon by U.S. astronauts and Soviet unmanned landers, laser instruments measure the earth-to-moon distance with less than 1 centimeter of error.

Scientists use even shorter laser pulses to observe the lightning movement of atoms, molecules, and chemical reactions. The pulses can, in effect, take “snapshots” quickly enough to prevent blurring. One laser system generates a pulse of just 6 quadrillionths of a second, fast enough to take step-by-step shots of a chemical reaction lasting only 100 quadrillionths of a second.

Lasers are also good for measuring very slow movements. Geologists use them to measure the almost imperceptible creep along the San Andreas Fault in California. A two-laser device on one side of the fault shoots red and blue beams at a reflector farther up the fault on the other side. One beam could be used to measure the distance. But by comparing two beams of different frequencies, geologists calculate how much the atmosphere has slowed the beams on a given day. With this information, they compensate for measurements taken under different atmospheric conditions. Shooting at a reflector 5 kilometers away, the instrument can detect a shift in the earth of only 2 millimeters.

The ability to develop lasers with special talents opened the door to their use in communications in the 1970s. The breakthrough came with development of a semiconductor laser that operates at room temperature, is smaller than a grain of sand, and produces a light frequency that travels well through glass optical fiber. This laser made it practical to use fiber-optic cables for long-distance telephone lines that carry thousands of calls at once. The installation of fiber-optic telephone cables since then has expanded long-distance telephone service and reduced its cost.

The semiconductor laser quickly became the key to compact disc (CD) recordings, which store large amounts of information and can be played at home. CDs were invented in the Netherlands, and the first audio CDs were introduced in Japan in 1982. Information for a disc is translated into the 1's and 0's of digital code and then stamped onto the upper side of the disc in a series of long pits. To read the information, a pinpoint laser beam scans the bumps on the underside. Flat surfaces between the bumps reflect a strong return beam; bumps scatter the light and weaken the beam. Sensors detect differences between strong and weak beams, interpreting them as digital code. Music, video, and computer data can all be stored in digital form on compact discs.

Other types of laser are especially useful for probing the environment. Government agencies and private organizations around the world use ground-based and airborne lasers to measure air pollution, monitor the weather, and study climate. Laser instruments have been used to study holes in the ozone layers over the North and South poles, particulates and gases over the Amazon rain forests, and dust drifting across the Atlantic from the Sahara.

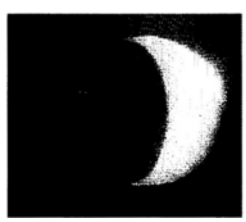
Laser radar, or *lidar* (*l*ight *d*etection *a*nd *r*anging), detects airborne particles of dust, moisture, and chemicals by measuring the strength of laser light reflected back to the instrument. These fine particulates are invisible to normal radar. Weather scientists use lidar plus knowledge of the Doppler shift to study wind speeds. Light reflected off particles moving with the wind changes frequency, which gets higher if the particles are moving toward the observer and lower if they are moving away. A similar frequency shift causes a train whistle to sound higher while a train approaches and lower as it speeds away.

Another system, called differential absorption lidar, uses laser beams at two frequencies to detect the presence of a gas in the atmosphere and measure whatever is there. The first beam uses lidar to measure the light reflected back by particulates. The second beam, at a wavelength absorbed by a gas such as ozone, scans the same area. Some of its light is absorbed by the gas but some is reflected back by particulates. The amount of gas in the air and its location are revealed by comparing the return echoes of the two beams.

In the future, laser research will aim at reducing the size and cost of lasers while expanding their versatility. Technology is being developed for arrays of tiny semiconductor lasers—which are limited in size—that develop enough power for devices such as printers and facsimile machines. The search for a powerful laser that can be tuned to many frequencies has sparked interest in the free-electron laser. This laser generates light by sending electrons through a periodically alternating magnetic field. Its periodicity or its strength can be altered to change the frequency of the light beam.

At the same time, existing lasers are being applied to many new tasks. Lasers will find use in industries seeking greater speed and efficiency. They fit well into automation schemes because they can be operated by computer and used by robots. And, because light beams are quickly redirected with mirrors and fiber-optic cables, lasers can be assigned new jobs without costly retooling.

The fastest growing field for lasers, though, is undoubtedly medicine. Lasers are being investigated for reshaping the cornea to correct eye problems. They are being tested for activating toxic anticancer drugs that accumulate in tumors but pass through the rest of the body. And lasers are being used experimentally for drilling new blood channels in weakened hearts and for other techniques aimed at reducing heart disease, the leading cause of death in the United States.

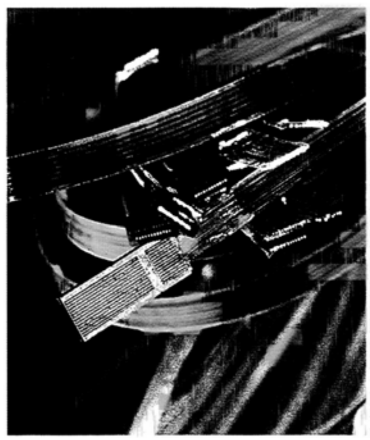


A laser beam shoots moonward from an observatory, left, in a test to learn whether a laser could hit a small target on the moon. Laser beams from this and another observatory appear as two tiny dots of light, above, sparkling on the dark side of the earth in a photo taken from the moon by a television camera on the *Surveyor* 7 lunar probe. This test led to the use of lasers for measuring the earth-to-moon distance.

9

Fiber-Optic Communication

The information revolution of the 1960s created such an avalanche of data that futurists saw it soon overwhelming the telephone lines and radio waves that carry information around the globe. That vision—and the invention of lasers—spurred research into the tremendous potential of light, which can carry thousands of times more information than either electric signals or radio waves. The work led in 1970 to a very transparent glass thread whose appearance quickly opened the door to fiber-optic communication, a technology able to channel the flood of information into the twenty-first century.



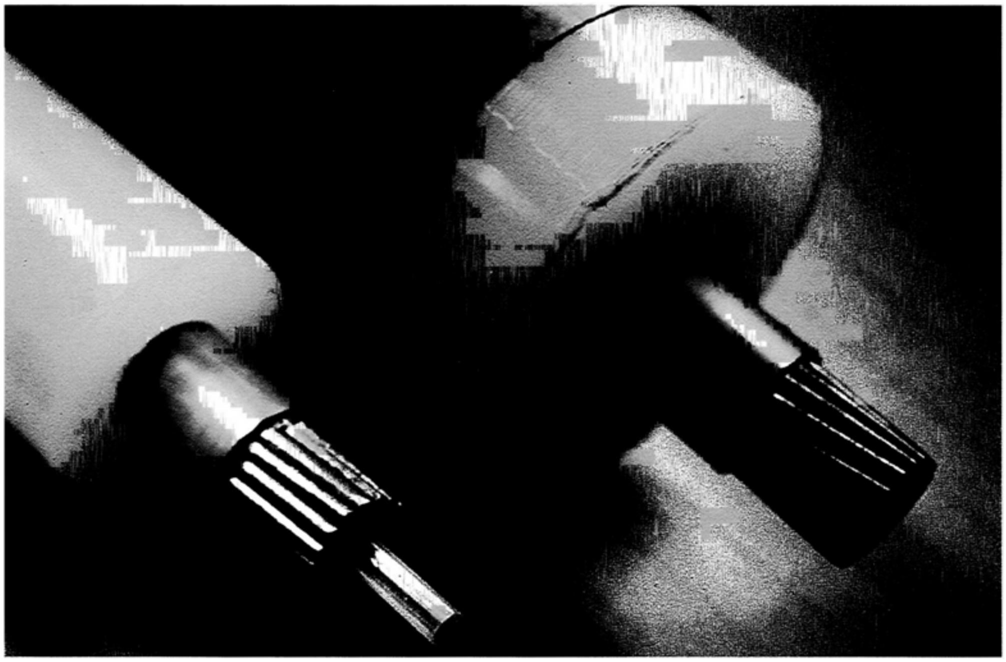
Right: Ultrapure glass fibers encased in protective ribbons are the mainstay of fiber-optic communication systems.

Today's optical fiber is thinner than a human hair. Yet it carries so much information that four fibers—two in each direction—in a trans-Atlantic telephone cable are handling up to 40,000 calls at once. The cable, called TAT-8 and laid in 1988, is the first transoceanic fiber-optic cable. TAT-7, the copper cable laid in 1983, carries less than a fourth as many calls and is twice as thick. The huge capacity of optical fibers translates into lower construction cost per telephone circuit. The first trans-Atlantic copper cable, for example, cost more than $1 million per circuit to install in 1956; 32 years later, TAT-8 cost less than $10,000 per circuit.

Waves of light carry more information because they have higher frequencies— measured in wave cycles per second, or hertz—than either radio waves or the electric waves on copper telephone wires. High-frequency waves can be switched on and off faster than low-frequency waves, so they can be divided into more pulses per second. The pulses and gaps between them represent the 1's and 0's of digital information. The infrared laser light used in optical telephone cables has a frequency of about 100 million megahertz, 100 million times higher than a typical AM radio signal and 100 billion times higher than an electric telephone signal.

The green light of a an argon laser flows through several miles of experimental optical fiber wound around a spool. Similar hair-thin optical fibers are the heart of cables that carry 40,000 or more simultaneous telephone calls on beams of laser light under oceans and across continents.

Fiber-optic communication became practical with the development of fibers that carry light pulses a substantial distance before needing a repeater. Their cores are made of silica glass, one of the most transparent solid substances known. Impurities in early glass fibers weakened pulses so much that light lost 99 percent of its energy after just 20 meters. But a new chemical process, pioneered in the 1970s, now produces cores of such high transparency that fibers in TAT-8 need only 101 repeaters to boost signals across the Atlantic. TAT-7, the copper cable, needs 662.



Below: Fiber-optic cables carry many more communication signals than do copper cables of similar size. Fiber cable laid in the trans-Atlantic link is less than half the size of copper cable used in an earlier link but carries more than four times as many telephone calls.

The C.S. (Cable Ship) *Long Lines* laid more than 3,600 miles of the TAT-8 fiber-optic cable, from the United States to a point off the coast of Europe. From there, British and French ships laid branch cables to their respective countries. In all, nearly 4,200 miles of cables were laid.

The debut of a practical fiber coincided with the development of other technologies needed for fiber-optic communication. In 1970 a room-temperature, semiconductor laser was built that could transmit well-defined pulses through long-distance optical fiber. Photodetectors were developed that could handle the torrent of pulses pouring out the other end and convert them into electric signals. For short-distance systems, tiny light-emitting diodes (LEDs) were devised that use less power and are less expensive than lasers. Although their signals deteriorate over long distances, LEDs are efficient for short links between, for example, a compact-disc player and stereo amplifier or computers in a local network.

Optical fibers can handle many times more information if they carry light pulses of several frequencies at the same time. The bandwidth of light (its range of frequencies) is about 10 billion megahertz from infrared to ultraviolet and can be divided into millions of signal channels, each at a slightly different frequency. Radio waves cover a relatively tiny bandwidth, leaving little room for multiple channels. The bandwidth is even smaller for electric channels.

Most optical fibers today carry light of only one frequency, although they are capable of transmitting several more. So far, it has proved economical to use multifrequency systems only in special cases of growing demand where limited numbers of fibers have already been installed. For example, fiber pairs that were carrying 24,000 voice circuits between Chicago and Philadelphia have been upgraded to transmit two frequencies, so they now carry 48,000 circuits.

Fiber-optic communication has other advantages over radio and electric channels. Light signals do not produce the external halo of electromagnetic waves that surround electric telephone lines and cause "cross talk" between them. Optical fibers are also relatively secure from unwanted eavesdroppers, who can easily intercept radio waves or tap electric telephone signals without being detected.

Optical fibers have been quietly weaving into communication networks since the first commercial system opened in Chicago in 1977. Since then more than 1.5 million miles of optical fiber have been installed across the United States; copper cables are no longer laid for main lines between U.S. cities. An undersea fiber-optic cable that U.S. and Japanese cable ships laid across the Pacific was activated in 1989. Optical fibers have also been adapted for sensing movement in gyroscopes, linking industrial lasers to cutting and drilling tools, and threading light into the human body for examinations and laser surgery.

A future engineering challenge lies in building a computer that uses light instead of electricity. Theoretically, an optical computer would be 1,000 times faster than the best modern supercomputers. Another challenge closer to home is in stringing fibers to individual users from the optical main lines that now exist. At present, copper wires connect homes to central telephone exchanges, where electric signals are converted into light pulses that are channeled into the main lines. Telephone authorities in the United States, Great Britain, Japan, France, Canada, and West Germany have been running optical fibers to homes on an experimental basis since 1980. Once economic and regulatory obstacles are overcome, the pace of replacing copper wires with optical fibers to individual homes in the United States should pick up. Economical optical switches and converters for such "end-to-end" systems still need to be developed. But early in the twenty-first century, many people could be enjoying hundreds of television shows, movies, newspapers, and books brought into their homes through a single, hair-thin optical fiber.

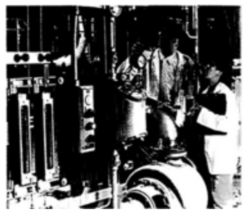
Left: Optical fibers can be threaded into the ureter, the tube leading from the bladder to the kidney, to bring in laser light that dislodges kidney stones. The photo here shows a laser chipping a kidney stone into fragments small enough to pass through the ureter naturally.

A technician in Philadelphia checks a device that uses microprocessors to pinpoint a malfunction among signal regenerators along the heavily used fiber-optics line between New York City and Washington, D.C.

10

Genetically Engineered Products

The first fruits of genetic engineering—the products made by organisms implanted with a foreign gene—have contributed handsomely to human welfare in the few short years since they appeared.



Technicians inspect the control unit at the bottom of a large-scale evaporator used in the final steps of purifying human insulin produced by genetically engineered bacteria.

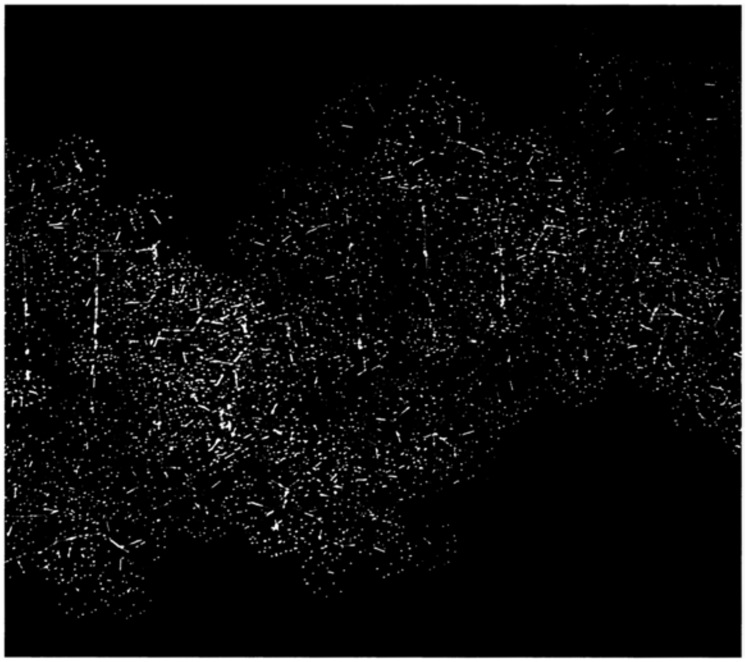
- Insulin, needed by millions of diabetics, has been produced commercially by genetically engineered bacteria since 1982. The product is identical to human insulin and so does not cause the allergic reactions sometimes produced by insulin derived from animals. Nor is its supply subject to the ups and downs of the livestock market.
- Human growth hormone (HGH), needed for normal physical development, has been available as a genetically engineered product since 1985. Previously, many of the more than 10,000 U.S. children low in HGH could not get treatment with the natural substance, which is extracted in tiny amounts from the pituitary glands of cadavers at autopsy. And in 1985, distribution of HGH from this source was stopped after evidence suggested it might be contaminated with a virus causing a rare, fatal disease. Today, however, there is plenty of pure biosynthetic HGH.
- Tissue-plasminogen activator, or t-PA, appeared as a genetically engineered product in late 1987. It quickly dissolves blood clots that cause heart attack and prevents their recurrence. It is already standard treatment for heart attack victims at hundreds of U.S. hospitals.

These and other genetically engineered products now available are created through the efforts of biologists and engineers. It is biologists who "engineer" new organisms by splicing a gene from one organism into another. Traditional engineers provide an indispensable bridge from biology lab to the public. They design and build the mechanical systems that allow the new organisms to grow in large quantities and that process the valuable substances the organisms produce. In addition, they develop complex laboratory instruments that simplify and speed the work of genetic engineering.

A genetically engineered product begins with biologists who find a gene that produces a valuable substance such as HGH. Using enzymes that dissolve bonds to neighboring genes, they cut the valuable gene out of the DNA, the genetic material of a cell. Then they insert this gene into another organism—such as the common bacterium *Escherichia coli*—that will multiply itself and the foreign gene along with it.

Once the genetically engineered "bug" has been created, engineers design a system in which its product can be produced and processed in large quantities at a reasonable cost. The production of human insulin, the first commercial product of genetic engineering, is a good example. It was developed in the United States and appeared commercially under the trade name Humulin, first in the

United Kingdom and later in the United States.

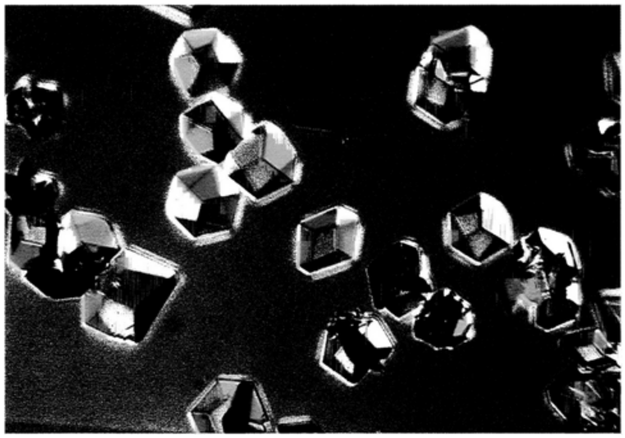


A spiraling chain of DNA, the genetic blueprint of life, shimmers in this computergenerated molecular model. Certain DNA segments make up the genes that produce insulin, human growth hormone, and other important substances.

The insulin molecule is composed of two parts called A and B chains. The original Humulin process used two versions of *E. coli* to produce the chains. One version contained a gene producing A chains and the other contained the B-chain gene. Each version was grown, or fermented, in a large separate tank. The chains they produced were extracted from the bacteria and purified. Afterward, A and B chains were combined in a third vessel. The complete molecules were then purified and crystallized into a usable form of human insulin.

The Humulin process demanded special engineering to handle the uncertainty surrounding the first large-scale use of genetically engineered microbes. Scientists in the late 1970s did not know whether such bugs might survive in nature and contaminate the environment. So the bacteria were grown in closed stainless steel tanks with the inflow of nutrients and oxygen carefully controlled by computer. Water vapor and carbon dioxide that flowed out were decontaminated. A special double seal was invented to prevent the escape of microbes from around the shaft of the paddle-like agitator that stirred the culture. And the tanks were designed to function under negative pressure—the opposite of conventional tanks—to suck back any bacteria that otherwise might escape. Engineers also developed a new pasteurization system hot enough to kill the bacteria as they were withdrawn from the tanks, but cool enough not to damage the A or B chains.

The big challenge in producing Humulin, however, was in scaling up production from expensive 10-liter batches in the laboratory to less expensive batches of 40,000 liters in the factory. The scaleup was particularly difficult because these bacteria store the A or B chains within themselves, unlike microbes that produce antibiotics and secrete them. Engineers devised a way to extract the chains by pressurizing the cells in a tank and then shooting them out into normal atmosphere, where the pressure change caused the cells to explode like balloons and release their contents. The chains were separated from cell debris in several steps ending with high-performance liquid chromatography. This laboratory technique is performed by pouring a mixture through a pencil-sized column of material that sifts out certain molecules. But for large-scale Humulin production, columns 10 feet tall and 12 to 16 inches in diameter had to be designed. Today, Humulin is produced by a similar, but more efficient process involving a new type of genetically engineered bacteria and only one fermentation tank.



The first insulin produced by bacteria implanted with human insulin genes was processed into crystals. The insulin must be separated from the bacteria and purified in relatively large quantities in order to be useful to many diabetics.

Potentially useful genes are often identified by analyzing the proteins they produce. A protein sequencer is used to determine the order of amino acids making up a chainlike protein molecule, thereby uncovering the identity of the gene that made it.

Traditional engineers are not directly involved in some other aspects of genetic engineering, such as the genetic alteration of plants and animals or the potential treatment of humans with genetic disorders. They are, however, becoming more involved with processing the products that are produced by genetically altered plants and microorganisms. Biologists are modifying organisms to produce everything from pharmaceuticals to food processing agents to specialty chemicals. In fact, the greatest use of genetic engineering in the future may be in the production of products that are now created by chemical processes, which often involve high temperatures and pressures as well as toxic by-products. Biological synthesis, on the other hand, usually takes place at room temperature under normal pressure and produces biodegradable waste.

In the meantime, people have already begun to investigate the use of genetically altered microbes to clean up toxic waste, degrade pesticides, or to turn organic waste material into useful products. They may one day use genetically altered bacteria to loosen underground oil so it can be pumped to the surface or to leach precious minerals from ore.

Perhaps the biggest contribution of traditional engineering to this field has been the development of instruments that speed the process of genetic engineering and expand its possibilities. Two devices—the protein sequencer and the DNA synthesizer— have already had tremendous impact on the detective work of genetic engineering. For instance, one biologist working with a DNA synthesizer can do the amount of work in one afternoon that would have taken 25 biologists five years to complete in the early 1970s.

The discovery of a valuable gene often begins with identifying the sequence of amino acids in the protein it produces. There are only 20 different amino acids. But the chainlike protein molecules have hundreds of amino acids linked in specific order. An instrument that can decipher this sequence appeared on the market in 1969. It is essentially a computer-controlled plumbing device that uses solvents to cut one amino acid at a time from the end of a protein molecule. Knowing the amino acid order, biologists can identify the gene that made the protein.

Another device, which entered the market in 1982, can actually build small genes or gene fragments out of DNA—the genetic material found in cells. A DNA synthesizer hooks together subunits, called bases, in the proper order for a particular gene or gene fragment. These synthetic genes and fragments can then be used for several purposes, including genetic engineering. For example, the genes that produce Humulin are really synthetic genes created by a DNA synthesizer.

The dream machine of genetic engineering, though, is a device that can rapidly sequence DNA, much as proteins are sequenced. Human DNA contains more than 3 billion bases, and today's DNA sequencers can analyze only about 9,000 bases per day. The challenge for today's engineers is to develop in the next four or five years machines that are at least 10 times faster than present sequencers.

The amount of genetic information already being generated by DNA sequencers is overwhelming. To check a new sequence against the massive, growing data bank of known sequences will require faster computer systems. One under development uses a series of 500 or more microprocessors that can each be programmed to recognize one of the four types of DNA base. Essentially, the series is programmed to reflect the order of bases in the new DNA sequence. As known sequences from the data bank flow past the series, each microprocessor "lights up" when its particular base passes by. When all light up together, they signal the location of an identical sequence in the data stream. Using this recognition system, the computer can search the DNA data bank for similar patterns thousands of times faster than existing computers.

For nine years, a deficiency in human growth hormone (HGH) stunted the growth of this California girl. But in her tenth year, injections of HGH produced by genetically altered bacteria stimulated a 5-inch burst of growth, catching her nearly up to the normal height of a girl her age.

Work is under way to determine the entire sequence of human DNA, called the genome, and map the location of all 100,000 or so genes. This data would reveal more about human biology and disease than has been learned in the past 200 years. Scientists and engineers would dearly love to map the entire human genome. With the right tools, they may soon do it. Completing the project would be, some believe, the biological equivalent of putting a man or woman on the moon.

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