OVERVIEW

Science after World War II

During World War II scientific development was vastly accelerated as a result of the war effort. Among the discoveries and inventions that reached practical application as a result of the war (although they all had roots in prewar research) were synthetic rubber, radar, DDT, penicillin, nuclear fission, jet-powered aircraft, helicopters, ballistic missiles, and the electronic digital computer. After the war, this technology quickly reached the public in developed countries. The cumulative impact of the advances changed the environment in fundamental ways. There had been no period of comparably swift technological change since the Industrial Revolution or perhaps not even since the adoption of farming some 10,000 years earlier.

In some cases, inventions or discoveries not directly involved with the war effort actually slowed rather than accelerated. One such example is that of television. But after the war, when the growth of television resumed, it quickly became ubiquitous in advanced countries.

Although the changes that occurred were phenomenal, the scientists of the time were not very good at predicting which changes would occur in the postwar period. Some said that helicopters would replace automobiles. No one foresaw that DDT would be banned in the United States after more than 20 years of use. The real significance of the electronic computer was misunderstood in the immediate postwar period (one prediction was that by the 1980s, a few large companies would own their own computers), while people expected nuclear power to solve all of the world's energy problems.

In pure science as well, the unexpected continued to occur. Few scientists in the brief optimistic period between the end of World War II and the start of the Cold War would have predicted that before the end of the century, our evolutionary history would be revealed in the test tube instead of in fossils; people would walk on the moon; the beginnings of the universe would be explained; the secrets of heredity would be unraveled; the discarded continental drift theory would resurface as the most vital part of earth science; many famous conjectures in mathematics would be resolved; the elementary particles would almost make sense; and solid-state devices would replace vacuum tubes in most applications.

Big science

The way science was conducted also changed after (in some instances during) World War II. Before that time, almost all advances could be ascribed to an individual working on his or her own or with a single partner or mentor. After World War II, it was the exception rather than the rule that a concept or device would be developed by a single scientist—except for studies of whole organisms and their behavior and for mathematics, which remained the preserve of the individual. In other disciplines, teams did it all.

There were good reasons for this shift. After 1945, it was not possible to have a major program in particle physics without expensive particle accelerators and detectors. To a lesser degree, similar equipment needs were felt in other "hard" sciences. Expensive equipment must be shared to be affordable. Even in the life sciences, the cost of science soared. By the mid-1980s the average grant from the US National Institutes of Health had reached $137,000 a year, paying for ever more complicated studies. In addition, a phenomenon often needed to be viewed from many angles before it could be understood. Interdisciplinary teams fulfilled this requirement.

Science became big in another way, also. There are far more scientists today, both in actual numbers and as a percent of the world's population, than there ever existed in the past. The reasons for this growth are complex. For one thing, the world's population is larger, and much less of it is needed to produce food and manufactured goods, freeing more of the population for other pursuits. More institutions perceived the need for scientists on their staffs. In the 1980s, half of all the scientists in America were employed in business or industry. Some large corporations, such as AT&T and IBM, even support their own basic research institutions. Government funding of science has made it possible for universities to have larger science

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departments and for individual scientists to make more money.

Furthermore, scientists at research institutions are writing more. Before the 1970s, top scientists usually wrote about two dozen articles in their scientific lifetimes. As competition for jobs increased among the scientists, each person felt the need to write more to make himself or herself more attractive to employers. In many cases, the results of research were broken into small bits with each published separately in one of the thousands of journals available by the 1980s. In a few cases, the same pressures resulted in fraud, as scientists published results without taking the time and effort to gather or analyze data.

Most scientists, however, were producing a lot of knowledge, so much that no one could keep up with the details and only a few generalists could even follow the major trends in all areas of science. This has resulted in another trend, specialization.

Specialization and changing categories

Over the history of science since the Renaissance, as the totality of scientific knowledge has grown, scientists have specialized more and more. Newton investigated all aspects of the physics of his time and also contributed greatly to mathematics. Einstein limited his work to theoretical physics, but he contributed to virtually all parts of that field. A theoretical physicist today must specialize in particles, materials, nuclear physics, astrophysics, biophysics, or perhaps just gravity. Only the very best, such as Enrico Fermi, can bridge the gaps between even two of these specialties. The same situation is true in other parts of science as well. A "whole-organism biologist," who studies such whole organisms as birds or plants and looks at behavior or anatomy or taxonomy, has little in common with a molecular biologist, who studies how events happen within cells. This kind of dichotomy was not so significant in prewar science.

At the same time as there has been specialization, there has also been a merging of disciplines. Astrophysics and biophysics are only two examples. Chemistry has been especially partitioned into new disciplines. On one side, chemistry has increasingly become a part of physics, as physicists have redeveloped chemistry from the proton, neutron, and electron on up to substances. In another direction, biologists have gradually moved into chemistry in their search for how living things work at the molecular level. One result is that much of what used to be chemistry is materials science (physics) and biochemistry (a part of biology). The leftover part is largely chemical engineering, for the theoretical part of chemistry has been taken over by the materials scientists.

In a few cases, new sciences have emerged that were not perceived as separate disciplines to any significant degree before World War II. Ecology existed, for example, but there were no professional ecologists as such; they were biologists who specialized in ecology. Ethology, the scientific study of animal behavior, and limnology, the study of lakes and freshwater systems, are similar cases. In physics, the separation of nuclear and particle physicists did not take place until after the war. Some astronomers (prewar) became cosmologists (postwar), and so did some physicists. Space science is still emerging. There are even sciences with nothing known at present to study, such as exobiology, the study of extraterrestrial living things.

New concerns

Although the growth of science would seem to suggest that most people regard science in a positive fashion, it is far from clear that that is the case. The development of nuclear weapons led to a perception by some of scientists as amoral seekers after knowledge. Among scientists themselves there was considerable horror at what they had accomplished. It was apparent that nuclear weapons could destroy life on Earth, especially after the development of fusion bombs. Some scientists formed the Union of Concerned Scientists to work against the misuse of nuclear energy. Others refused to work on defense-related projects. The public perception of nuclear energy as dangerous was further enhanced by a number of accidents in nuclear power plants; the most spectacular, in Chernobyl in the

Soviet Union, killed a few dozen people outright and may have caused cancer in hundreds more. Around the same time, interdisciplinary studies of the effects of nuclear war began to predict periods of total darkness, or rain with the strength of battery acid, in addition to the problems of radioactive fallout.

But it was not only nuclear energy that was perceived as dangerous. Probably as a result of the concerns about nuclear energy, other parts of the scientific endeavor were also viewed with suspicion. The unsophisticated worried that space travel was affecting the weather, while the somewhat more sophisticated worried that genetic engineering would accidentally loose plagues upon Earth. Before 1946, nearly everyone seemed to think that science was ultimately beneficial, although a few (such as Aldous Huxley, who wrote *Brave New World* in 1932) were concerned. After 1945, many people were no longer sure that science would ultimately benefit humankind. A growing number worried that it would destroy it.

Major advances

Anthropology and archaeology. Physical anthropologists discovered two previously unknown species of hominid, one definitely on the line to modern humans (*Homo habilis*) and the other possibly ancestral to that line (*Australopithecus afarensis*). By the mid-1980s, nearly complete skeletons of both species were known. Skeletal remains of modern humans dating back almost 100,000 years were also found. But much of the excitement in physical anthropology was about molecules, not bones. Starting from a suggestion of Linus Pauling, a host of investigators used proteins and DNA to analyze the relationship of humans to the great apes. The results of this molecular approach—mainly that humans and chimpanzees, especially pygmy chimpanzees, are more closely related than chimpanzees or humans to gorillas, orangutans, or gibbons, and that the split between the human and ape lines took place only a few million years ago—were

Discovering DNA

Today it is common knowledge that DNA, a nucleic acid, directs the development of cells. Scientists gradually learned about DNA in a curiously twisted fashion that is commonplace in science. For one thing, the discovery of DNA required progress on three separate fronts: cytology (the study of cells through a microscope), genetics, and chemistry.

After Gregor Mendel's laws of heredity were rediscovered in 1900, considerable interest developed in what causes heredity. The fundamental structures involved—the chromosomes—had been discovered and studied by Walther Flemming in the 1880s, but no one knew that they were connected to heredity. They were just long thin structures that appeared when cells were stained during cell division. Also, Friederich Miescher had discovered nucleic acids in cell nuclei as early as 1869, but they were not connected either to heredity or to chromosomes—although Miescher's later discovery that salmon sperm are almost entirely nucleic acid plus a simple protein should have been a clue to the connection with heredity.

In 1907 Thomas Hunt Morgan, who was somewhat skeptical about genetics, began to use fruit flies in breeding experiments. Within a short time he found that Mendel's laws worked, but also that some inherited characteristics appeared to be linked together. These linkages behaved as if the units of heredity, the genes, lined up in long rows. A suitable long thin part of the cell that could physically contain the genes was the chromosome, as had earlier been suggested on other grounds by August Weismann. By 1911 Morgan was able to show that genes strung along the chromosomes are the agents of heredity.

While this development was occurring on the genetic front, there was also some progress being made in chemistry. In 1909, Phoebus Aaron Theodor Levene was the first to determine that nucleic acids contain a sugar, ribose. Twenty years later, he found that other nucleic acids contain a different sugar, deoxyribose. Hence, there are two types of nucleic acid: ribonucleic acid (RNA) and deoxyribonucleic acid (DNA). Levene also worked out the chemical nature of the other compounds that were in RNA and DNA. This chemistry was then explored in detail in the 1930s by Alexander Todd.

Chromosomes, like other cell structures, contain proteins. They also contain DNA. Proteins were known to be complex molecules that are biologically very active, so everyone thought that genes must be proteins—until 1944 when Oswald Avery and coworkers showed that hereditary characteristics could be induced by pure DNA, without a protein involved. He showed that genes must consist of DNA in some way.

By the early 1950s a few scientists from the different fronts were tackling the problem of understanding DNA. Among these was Linus Pauling who was at the time probably the most accomplished chemist. In 1951, Pauling, working with B.B. Corey, determined that the structure of a class of proteins is a helix, which is a three-dimensional spiral. This was the first determination of the physical structure of a large biological molecule. At about this time, Pauling turned to the study of DNA, hoping to discover its structure as well.

In England, there were several scientists interested in the structure of DNA. Maurice Wilkins and Rosalind Franklin were doing X-ray diffraction studies of DNA in hopes of elucidating its structure. Diffraction studies had proved successful in analyzing crystal structures, and DNA could be crystallized. The complexity of DNA was a frustration, even as Franklin produced better and better photographs showing the diffractions.

Another English scientist interested in the subject was Francis Crick, a 35-year-old graduate student. With an undergraduate degree in physics, he too would have liked to do X-ray diffraction studies; but English custom kept him from competing with Wilkins and Franklin. Instead, he just thought and talked incessantly about DNA.

Discovering DNA (continued)

A fourth interested scientist was James Watson, an American. Watson was working as a postgraduate student, trying to learn about genetics from studying organisms. But he realized that the true solution to the problem was more likely on the chemical front, so he abandoned what he was doing and applied for work in X-ray diffraction. He was lucky to be taken on at the same Cambridge laboratory where Francis Crick was pursuing his degree, not far from London, where Wilkins and Franklin were working.

News of Pauling's discovery of a helical structure in proteins set all of the English group (except Franklin) thinking that DNA might be a helix as well. Wilkins thought it might be several helices twisted together.

Watson and Crick decided to try using the method by which Pauling had found the helix in proteins. He had stuck together models of the subunits of the molecule, rather as one puts a tinker toy set together. The models need to be constructed so that they fit together according to Pauling's theory of the chemical bond. Watson and Crick acquired a copy of Pauling's 1939 book on the chemical bond and came up with a model for DNA of three helices twisted together. But when they showed it to Wilkins and Franklin, Franklin pointed out that it disagreed with her diffraction data and had other deficiencies as well.

Watson gradually learned to do X-ray diffractions and established to his and Crick's satisfaction that DNA does have a helical structure. Crick figured out that the bases in DNA are always paired in the same way. Franklin insisted on the correct location of the sugars, which Watson and Crick ignored.

Meanwhile, Pauling produced two versions of his model of DNA. It contained three twisted helices and was clearly wrong. One of the best chemists of the century had made a mistake in his chemistry.

After another false step, Watson finally built a model that incorporated two helices, paired bases, and the sugar structure recommended by Franklin. Crick did calculations that showed that this model was feasible. Wilkens and Franklin produced X-ray diffraction calculations that confirmed the structure. On a visit to Cambridge, Pauling agreed.

The true nature of DNA had finally been discovered. Watson, Crick, and Wilkins won the Nobel Prize a few years later (Franklin died before the prize was awarded, and was thus disqualified). By then, Pauling already had a Nobel Prize for Chemistry for his work on chemical bonds; that same year he won a Nobel Peace Prize for his opposition to atmospheric nuclear weapons testing.

gradually accepted by the more traditional physical anthropologists. Before the molecular results were available, most anthropologists believed *Ramapithecus*, an ape that lived as long as 30 million years ago, to be our most recent common ancestor.

Other theories of physical anthropologists also changed greatly during the period. Before World War II it was generally assumed that the main characteristic of hominids was the large brain relative to the body. In part this was based on the Piltdown hoax, which combined a modern human brain with an orangutan jaw, and on human vanity. When Piltdown man was discredited in 1953 and evidence accumulated that the small-brained australopithecines walked erect, the definition of hominid shifted from the brain to the legs and pelvis. Most physical anthropologists of the 1960s believed that the australopithecines gradually evolved into the earliest humans; but the discovery in the 1970s that the earliest humans and australopithecines occupied the same territory at the same time changed that idea. The known australopithecines and humans must have a common ancestor (now believed by some anthropologists to be *A. afarensis*). In the 1980s the idea that early humans were hunters began to give way to the idea that they were scavengers.

Archaeologists made several striking finds, including an ice-age religious sanctuary, boats designed to carry an ancient Egyptian pharaoh's soul to heaven, and armies of statues guarding the tomb of the first emperor of China. One of the main trends in archaeology emerged from the invention of better diving equipment by Jacques-Yves Cousteau. Scuba gear made it possible for archaeologists to expand their work into the sea, where many essential artifacts and even whole villages have been preserved. Increasingly, archaeologists took care to see that their work was scientifically valuable and not just a search for trophies and treasures. For example, parts of sites were deliberately left untouched so that future generations of archaeologists, who might have better tools, could investigate the undisturbed portions.

Astronomy and space. Although all phases of astronomy have advanced continuously since World War II, it is convenient to relate the advances by decade. In the 1940s, the Hale telescope was put into operation at Mount Palomar in California. As of this writing, it is still the best optical telescope in the world, although that will change in the 1990s. In the 1950s radio astronomy began to probe the universe, which was found, by other means, to be twice the size scientists had thought it was. It was not clear in those days whether the universe existed in a steady state with continual creation of matter or whether it had begun in a Big Bang. The 1960s saw the first exploration of nearby space with satellites and spaceprobes, as well as the surprises of quasars and pulsars. The Big Bang theory of creation became dominant as new evidence surfaced. X-ray and neutrino astronomy joined optical and radio approaches. In the 1970s, theoretical physics and astronomy, always close, became even closer. There was a lot of interest in black holes, objects so massive and dense that nothing, not even light, can escape their immediate region as a result of their immense gravitational forces. The 1980s added space-based infrared telescopes to the available ways of knowing the universe, while the Voyager spacecraft extended our close-up knowledge of the solar system to the outer planets. The inflationary universe helped make sense of the Big Bang. A major event in 1987 was the viewing of the closest observable supernova since 1604. Various studies found planets or other objects orbiting stars. These ranged from clouds of particles to brown dwarfs—objects too large to be called planets but too small to become stars.

From tubes to chips

While Thomas Alva Edison is remembered mainly as an inventor, he also made one extremely useful scientific discovery in 1883, now known as the Edison effect. He found that electricity flows through space from a heated metal. When the electron was discovered, the Edison effect was explained as electrons boiling off the metal, like water vapor from a heated tea kettle. Sir John Ambrose Fleming in 1904 developed the first practical application of the Edison effect; he found the electrons traveled only to a positively charged anode. Since alternating current switches back and forth from negative to positive, the Edison effect could be used to turn alternating current into direct current. A device that does this is called a rectifier. Some electrical equipment, such as a radio receiver, will not work with alternating current, so rectification is needed when alternating current, which is more easily transported over long distances than direct current, is used as a power source.

The Edison effect is much more effective in a vacuum, so Fleming's device was enclosed in a partially evacuated glass tube. In America, such a device is still called a tube (in England, it is a valve). Later inventors, notably Lee De Forest, found other ways to use the Edison effect in tubes. De Forest showed how to use tubes as amplifiers, for example.

De Forest's tubes greatly improved the radio, which had previously relied on crystals for rectification. It was not clear why crystals could change alternating current to direct. When tubes came along, almost no one bothered to wonder why.

Tubes do not depend merely on the flow of electricity, as previous devices, such as the electric motors, lights, or heaters, do; instead, they depend on control of the behavior of electrons. Therefore, we speak of devices that use tubes as electronic, not merely as electrical.

Tubes made possible such electronic devices as radio and television, but they had drawbacks: heating a metal eventually causes it to boil away; the vacuum also tends to degrade; the power required for the Edison effect is fairly high; heat tends to build up in the vicinity of the tubes; and practical tubes have to be fairly large. While these problems were only a minor annoyance in building radio and television sets for the living room, they limited the size of portable sets. Also, when the first digital computers were built at the end of World War II, the many tubes needed used enough power to cause lights to dim. In addition, the computers produced immense amounts of heat that had to be got rid of, they occupied large rooms, and they failed with such frequency that it was clear that larger computers could never be built.

Although almost no one wondered why crystals worked as rectifiers, scientists at Bell Laboratories decided in the 1940s that it was worth looking into this question. One of them, William Bradford Shockley, found that some crystals worked better than others. The ones that worked best were impure crystals of germanium. By 1948, Shockley, abetted by theoretical physicists John Bardeen and Walter Brattain, was able to modify the impurities to produce crystals that were as good as rectifiers as tubes. They could also be used like a De Forest tube for amplification. The physicists called their new crystals transistors.

The transistor had none of the problems of the tube. It was small, needed no vacuum, did not wear out easily, and produced little or no heat. Soon transistor radios were the rage. The scientists won the 1956 Nobel Prize for Physics. Large commercial computers, starting with Remington-Rand's UNIVAC, could be built.

What people did not fully realize—except for a few penetrating thinkers like Richard Feynman—was that the transistor was just the beginning. The transistor works because it is possible to adjust the impurities in a crystal so that one region has an excess of electrons while another has a deficit. Electrons will flow from one region to the other just as electrons cross the space between the cathode and anode in a tube. But there is no need for heat to be used; and since this is all happening at the molecular level, not a lot of space is required. A transistor can be made very small indeed. In fact, a transistor can easily occupy just a small region on a crystal. So, you can put more than one transistor on each crystal.

And that is what scientists did. Beginning in the 1960s, ways were found to pack more and more transistors onto a given piece of crystal. Such a piece came to be called a chip. A chip is usually a fingernail-sized sliver of silicon, "doped" with impurities in a pattern that enables it to serve as a computer memory or a central processing system or a controller of fuel injection in an automobile. The chip has made possible the incredible increase in power and availability of the personal computer. It has also invaded almost all aspects of daily life, controlling everything from your microwave oven to your car.

Space travel is an entirely new technology whose first real successes occurred during this period, although it was foreshadowed by rocket research before World War II. Since 1957, when the first artificial satellite was put into orbit about Earth, space technology has been most useful as a scientific tool when vehicles without people aboard were used. Small spaceprobes reached Venus, the moon, and Mars. Others passed by Mercury, Jupiter, Saturn, Uranus, and Comet Halley (with Neptune about to be added to the list). Satellites detected belts of radiation around Earth, the solar wind, and giant magnetic fields in space.

At the same time, much of the public's interest was in

History of the computer

In the history of technology, the development of computers is unique. No other technical device underwent such rapid development after its invention.

For a long time scientists have been fascinated by machines that would be able to perform calculations. During the seventeenth century, Blaise Pascal invented a machine with geared wheels that could add and subtract. Gottfried Wilhelm Leibniz, a few years later, developed one that could add, subtract, multiply, and divide. These machines, and others like them, required that a human operator direct the operation at every stage.

In the nineteenth century, the Englishman Charles Babbage designed, but never completed, a working model of a different kind of computing machine, called the Analytical Engine. It had an important feature of the present-day modern computer: it was designed so that it would perform mathematical operations from a set of instructions or a "program" supplied to the machine. The machine would "read" the instructions from perforated cards similar to those that controlled the looms that had been developed by Joseph-Marie Jacquard about 20 years earlier. The Analytical Engine was to be equipped with a memory, which Babbage called the "store," and a central processor, which he called the "mill." A long sequence of different operations could be performed with no human intervention after the punched cards were fed in.

One reason the Analytical Engine was never completed is that it operated mechanically and technicians could not produce sufficiently accurate parts for mechanical operation. The invention of the vacuum tube, however, led to a revolution in technology during the 1920s. During the 1930s scientists investigated how the vacuum tube could be used to replace the mechanical gears and levers in the calculators of the day, descendants of Pascal's and Leibniz's machines.

Although it is unclear who really can be considered to be the "inventor" of the modern computer, it is now generally accepted that the theoretical physicist John V. Atanasoff and his assistant Clifford Berry in 1942 built the first operational computer that used vacuum tubes to perform mathematical operations. It was called the Atanasoff Berry Computer, or ABC. The ABC used binary numbers that were stored in capacitors mounted on a rotating drum; it could perform operations with 16-digit binary numbers, which correspond to eight-digit decimal numbers.

Around the same time, several other scientists and engineers started devising and building electronic computing machines. As was the case for many inventions, the development of computers was accelerated because of defense needs. During World War II, the Ballistic Research Laboratory in Aberdeen, MD, needed a faster, nonmechanical computer to keep up with the calculations of trajectories of projectiles that were required for the firing tables for gunners. Construction of the computer, known as the ENIAC (electronic numerical integrator and computer), began in 1943 and was completed early in 1945. The computer contained about 18,000 vacuum tubes, whose heating filaments remained switched on to reduce tube failures. Unlike Atanasoff's machine, the ENIAC was a decimal machine, but it was an important improvement because it was programmable and could function as a general purpose machine. The programming, however, consisted of changing the wiring of the machine by plugging cables into plugboards and setting thousands of switches. Setting up the machine for a new calculation was a long and arduous task.

The completion of ENIAC's successor, the EDVAC (electronic discrete variable computer), was delayed until 1952 because of legal battles concerning the patent. It incorporated many of the ideas of the mathematician John von Neumann. An important innovation was that programs could be stored in memory. Contrary to the ENIAC, which had several specialized processor units, the EDVAC had a central processor and a random-access read-write memory. It processed binary numbers serially and its functioning was based on Boolean logic.

In England, the development of electronic computers also started because of the war effort. During World War II, Germany used an electromechanical coding machine called "Enigma" that produced coded naval messages believed to be unbreakable. In Bletchley Park, a secret installation, the English built a series of electronic machines, named "Colossus," that could decipher the German secret messages. Ten versions were built, starting in 1943. The experience gained with the Colossus enabled the English engineers, under the leadership of the mathematician Alan Turing, to complete the ACE (automatic computing engine) in 1950. Turing wrote for that machine the first programs in the modern sense. They consisted of partially numerical and partially alphabetical code. A larger machine, the Mark 1, was completed in Manchester in 1948. It became the first computer operating on a program fully stored in memory.

During the 1950s and 1960s, the development of computers took off swiftly. The main hardware improvements were the introduction of the transistor to replace the vacuum tube and the introduction of integrated circuits to replace the circuits made up of discrete components such as transistors, resistors, and capacitors. The memories of computers also evolved from bulky cathode-ray tubes and delay lines via magnetic core memories to solid-state memories. Punch cards, like those planned for the Analytical Engine, and punch paper tape were first used for input and output and mass storage. These were eventually replaced by magnetic tape and magnetic disks. The development in hardware was such that the present-day desktop computer surpasses in memory, speed, and power the large mainframe computers from the 1950s and early 1960s.

The software also underwent an evolution from simple machine-code programs to the present-day high-level languages. Progress in the development of high-level languages and artificial intelligence suggests that computers programmable in plain English will be a reality in the near future.

programs that put people in space. From the first flights in 1961, the adventure (and occasional disaster) of human space travel has been the focus of much of the space programs of both the Soviet Union and the United States. The US program first focused on putting people on the moon. It succeeded in 1969, although the project was abandoned after a few additional trips. Later the US program concentrated on the development of a system in which most of a vehicle could be used in the way that an airplane is. The US space shuttle program was closed down for a couple of years as a result of the *Challenger* accident, in which the vehicle exploded and killed all seven aboard. The Soviet Union so far has had a manned program directed toward the establishment of a permanent station in orbit around Earth. As a result, many Soviet cosmonauts have spent months at a time in space. The United States is planning to develop a space station as well, while the Soviet Union is beginning to develop a version of the space shuttle.

Space technology has had a number of direct benefits for people around the world. Communications satellites have helped make Earth a "global village." Weather satellites have given us the almost credible five-day forecast and have informed scientists about changes in the atmosphere. Resources satellites detect changes in forests and crops and locate mineral deposits. Satellites used for location of exact positions on the surface of Earth not only help ships and planes, but can even be used to find lost or injured individuals in a wilderness. Less appealing to many is the knowledge that the military forces of both the United States and the Soviet Union use satellites for spying and have vast numbers of space-going rockets armed with fusion bombs to use as weapons.

Biology. It can be argued that biology made the most dramatic progress of any science after World War II, especially biology at the level of the behavior of individual molecules. There were also dramatic gains in understanding the behavior of animals, especially primates, that emerged from careful studies in the wild. Mathematics was employed extensively by ecologists to describe the statistical behavior of communities of animals and to explain altruism and other traits in the controversial new discipline of sociobiology. The most notable development in biology, however, was the rise of genetic engineering.

A little more than 50 years after biologists became aware of Gregor Mendel's laws of heredity, James Watson and Francis Crick found the key to how these laws work. About the same time, scientists experimenting with bacteria and viruses that prey upon them discovered ways to transfer genetic material from one organism to another. The combination of new understanding and new techniques created the sudden growth of genetic engineering (see also Medicine below). Equally important, genetic information could now be used to learn about how proteins are built and what they do.

Chemistry. Although of little immediate practical use, the most dramatic story in chemistry was success in forming compounds with some of the noble gases, heretofore believed not to enter any form of molecule. Chemists are still working on making compounds with the remaining noble gases, with compounds of helium as the main goal. There is even some promise that the noble-gas compounds may have a role in the production of powerful lasers.

To many people chemistry gradually changed from friend to enemy in the postwar period. As chemists developed new herbicides and pesticides, they helped create the immense production of food and fibers with greatly decreased labor; but as fish kills and occasional problems with cancer among some who worked with the chemicals impinged upon people's consciousness, many felt it necessary to reduce the dependence on such chemicals. Similarly, chemists developed additives that prolonged food shelf life, made it cheaper, or improved its color; but again people came to view such additives with suspicion as part of a broad-based concern about the health risks of chemicals. More subtly, the chemistry that produced improved forms of Teflon also yielded the spray propellants and refrigeration gases that seem to be destroying the protective layer of ozone in the atmosphere.

Earth science. The period after World War II saw a revolution in our basic understanding of Earth's crust. In the 1950s and 1960s, geologists developed the idea that the crust of Earth was broken into a number of large plates that move relative to each other. This theory explained such features of Earth as the locations of many earthquakes and volcanoes, of most mountain ranges, and of trenches and rifts on the floor of the ocean. Although some geologists did not accept the theory at first, by the late 1980s there was firm evidence that the plates were moving in the predicted patterns.

Paleontology, although a study of once living creatures, is usually treated as part of earth science. A major controversy in paleontology arose in the 1980s following the discovery of a worldwide layer of iridium precisely at the boundary between the Cretaceous and Tertiary periods, a time of numerous extinctions.

Meteorology is another part of earth science. While weather forecasts improved as a result of data from satellites and radar as well as better computers and computer models, in 1961 Edward Lorenz established that very small changes in initial conditions result in large changes in the weather. Consequently, medium-term weather prediction (more than a week and less than a year) probably can never be certain. Scientists studying long-term changes, however, became concerned that gases released by human activity were causing major changes in the atmosphere. One such change, the greenhouse effect, may cause temperatures to climb worldwide as a result of carbon dioxide and other gases that trap heat in the atmosphere the way that the glass walls and ceiling of a

Genetic engineering

Genetic engineering consists of a set of methods to change the genes of an organism so that proteins produced by that organism differ in type or quantity from those produced by a "wild" organism—one that has not been altered. Although people have been causing such changes in organisms since domestication began about 10,000 years ago, the phrase *genetic engineering* conventionally refers to a set of techniques that only became possible in 1973.

It is easy to think that genetic engineering was the inevitable outcome of the Watson-Crick explanation of the mechanism of heredity in 1953, but that is not really the case. While knowledge of DNA structure and the genetic code is essential to genetic engineering, the path that led to practical results was separate from the path that led to understanding. Along the way, of course, both paths interacted constantly. The path that led to practical applications could not have been predicted in advance, as almost all of the important discoveries were previously unsuspected by any scientist.

The start of the path toward genetic engineering occurred in 1952 when Joshua Lederberg discovered that bacteria, like some protists, conjugate to exchange genetic material. This behavior, much like sex in multicellular organisms, led Lederberg to perceive that there are two populations of bacteria, which he called M and F. The F population contains a body that he called a *plasmid.* After conjugation, the F bacterium passes the plasmid on to the M bacterium, with which it has conjugated. (It would appear that Lederberg had his sexes backward, but that is not essential to what follows.) This discovery was completely surprising.

The next year William Hayes established that the plasmid consists of genetic material. By then it was clear that genes were DNA; therefore, plasmids were rings of DNA floating free of the main DNA in the chromosome of a bacterium.

About the same time, an apparently unrelated situation became a major problem. Both the sulfa drugs and the antibiotics of the late 1930s and 1940s were, in the 1950s, beginning not to work as well. Many bacteria were becoming resistant to these drugs. Epidemics, especially in hospitals, could no longer be controlled. Many scientists studied the problem. In 1959, Japanese scientists discovered that the genes for drug resistance were carried on plasmids, and therefore passed from bacterium to bacterium. Within a given bacterium, the plasmids multiplied, so there were plenty of copies to pass around. Putting a few drug-resistant bacteria into a colony of bacteria that showed no resistance resulted in short order in a colony that was completely resistant.

It is not surprising that some bacteria had plasmids that protected against these drugs. Antibiotics are natural substances found in the environment, so some bacteria have evolved defenses against them. The increase in the amount of antibiotics caused by human intervention led to the resistant bacteria passing the plasmids around to larger populations.

In the meantime, another line of research was also leading toward genetic engineering. Starting right after World War II, a number of biologists made an intensive study of viruses that infect bacteria, which are collectively called bacteriophages, or just phages. This line of research demonstrated that genes are DNA and not a protein, as had previously been suspected. As early as 1946 Max Delbrück and Alfred Hershey independently showed that the genes from different phages could spontaneously combine. Werner Arber studied the mutation process in phages in detail. In the process he discovered that bacteria resist phages by splitting the phage DNA with enzymes. Subsequent recombination of split genes was a consequence of this. By 1968, Arber had located the enzymes produced by bacteria that split DNA at specific locations. The split ends are "sticky;" that is, different genes that have been split at the same location by one of these restriction enzymes, as they came to be called, will recombine when placed together in the absence of the enzyme. The resulting product is called recombinant DNA.

The following year, 1969, Jonathan Beckwith and coworkers became the first to isolate a single gene. It was a bacterial gene for a part of the metabolism of sugar.

In 1973 Stanley H. Cohen and Herbert W. Brown combined the restriction enzymes with plasmids with isolation of specific genes to introduce genetic engineering. They cut a chunk out of a plasmid found in the bacterium *Escherichia coli* and inserted into the opening a gene from a different bacterium. Then they put the plasmid back into the bacteria *E. coli*, where copies were made and transferred to other bacteria. Within months other scientists repeated the trick, inserting genes from fruit flies and frogs into *E. coli.*

Not all scientists thought this was a good thing. In July 1974, Paul Berg and other biologists met under the auspices of the US National Academy of Sciences to draw up guidelines that would prohibit certain kinds of genetic engineering.

Since 1974, the tension between those who are rapidly advancing genetic engineering and those who worry about where it is going has continued. By the 1980s, the genetic engineers were producing useful products from bacteria and yeasts, including human growth hormone, human insulin, and a vaccine for hepatitis B. All these are made in tanks in controlled environments and have ceased to evoke much resistance from scientists or the public. There has been more resistance to experiments in which genetically engineered bacteria are released in the environment, although a number of small-scale releases have so far not resulted in known environmental damage.

In one area, the progress of genetic engineering has been frustratingly slow. From the beginning of the new technique, there has been hope that it could be used to cure human genetic diseases. So far, that has not proved possible. On the other hand, some of the techniques used in genetic engineering have made it possible to find genes that are markers for a number of diseases.

greenhouse trap heat. Another change is the thinning or loss of the ozone layer that protects life from excessive ultraviolet radiation; this change is caused by gases that catalyze ozone, an oxygen molecule of three atoms, back into ordinary oxygen, whose molecules have two atoms.

Mathematics. Although much of mathematics after World War II became so abstract that nonmathematicians had great difficulty following the results, some important proofs of long outstanding problems were produced. These include the proof of the long-standing conjecture that only four colors are needed to color any map. Another remarkable proof of a well-known conjecture, Mordell's conjecture, was made by Gerd Faltings in 1983.

For another conjecture, Paul Cohen showed in 1963 that Cantor's continuum hypothesis concerning infinite sets is neither consistent nor inconsistent with the generally accepted basis of mathematics. Cantor had discovered late in the nineteenth century that there are many different-sized infinities. His continuum hypothesis conjectured that two particular infinities constructed by different processes are the same size. Cohen's work (which was built on a 1940 proof by Kurt Gödel) showed that one can choose whether the two infinities will be equal or not equal. At the same time, Cohen (again building on Gödel's earlier work) showed that a widely used axiom in set theory has a similar position in mathematics.

More important than proofs of individual theorems was the development of fruitful new concepts in mathematics that could then be used to solve a range of problems. Most important of these is probably catastrophe theory, originally put forward by René Thom. Instead of dealing with smooth processes, such as continuous acceleration, catastrophe theory treats events in which "the straw on the camel's back" causes a complete change of state. Closely related to catastrophe theory is the theory of strange attractors, sets connected to unstable functions that have stable values near one or two points. Another fruitful new idea is fractal theory, originally put forward by Benoit Mandelbrot. A fractal is a figure that is self-similar at varying scales.

Medicine. The interaction of medicine and biology, especially molecular biology, became so close in recent years that it is sometimes difficult to tell where one ends and the other begins. On the other hand many innovations are pure medicine with little or no input from molecular biology. These include organ transplants; endoscopy and related techniques (for example, angioplasty, in which a tube inserted into an artery carries a balloon or laser used to flatten or remove arterial plaque); amniocentesis and other methods of diagnosing and treating the fetus; ways of handling fertilized human eggs to produce viable children; artificial substitutes for skin; cochlear implants to aid hearing; kidney dialysis; ultrasound scanning; and a variety of new vaccines.

The new technology of genetic engineering yielded various direct applications, including the production of certain proteins needed by some ill people (human insulin, human growth hormone, interleukin 2, and T.P.A., a blood clot dissolver); artificial vaccines, such as a safer and cheaper vaccine for hepatitis B; improved tissue matching capabilities for transplants; and the ability to locate gene markers for such genetic disorders as Huntington's disease or Duchenne muscular dystrophy.

Just as the discoveries of the endocrine system and of vitamins in the earlier part of the twentieth century revolutionized the understanding of disease, a new understanding of the immune system that developed after 1945 also produced major changes in our understanding of how some diseases are caused and how they may be avoided. The discovery of blood types, artificial immunity with killed or weakened germs, and allergic shock in the late nineteenth and early twentieth centuries suggested that some substances or processes in the body become activated when exposed to "foreign" proteins. After the war, Frank Burnet and Peter Medawar showed that the reaction against foreign proteins is developed largely after birth. The study of the immune system after this unraveled an increasingly complex network of interacting cells and proteins. Many diseases, including some types of arthritis and diabetes, were found to be caused when the immune system attacks a part of the self. Ironically, just as studies of the immune system began to reveal how it works, AIDS, the disease that destroys the immune system, surfaced.

A related development that has major implications for the future and many immediate applications was the invention of monoclonal antibodies. These molecules can be targeted on one specific receptor—part of a molecule. The monoclonal antibodies detect the presence of their target receptor and attach themselves to it.

Physics. World War II ended with two nuclear fission bombs ("atomic bombs") used as weapons, preceded by a single test earlier in 1945. Physics clearly had an important place in military matters, and funding for large projects in physics has continued, especially in nuclear and particle physics. More recently, governments have realized how important materials science is to them and the economy; this branch of physics has produced the transistor and its descendants, the laser, and the promise of high-temperature superconductivity. Funding for physics has contributed to a remarkable period of growth since the war.

Discovery of the Lamb shift in 1947, just before a major conference of leading physicists at Shelter Island, NY, led to the solution of mathematical problems that had surfaced in the study of atoms and subatomic particles. The mathematical theory that resulted is quantum electrodynamics (QED), often called the most accurate theory in physics.

Just as QED was being developed, however, scientists studying cosmic rays began to find new subatomic particles that did not behave as predicted—for one thing, they did not decay into other particles as fast as theory called for. The reason for this strange behavior was worked into theory and christened "strangeness," the beginning of a trend in physics toward whimsical names, from quarks and flavors to WIMPs (weakly interacting massive particles). Strangeness and the newly discovered strange particles were fit into a classification scheme, somewhat like the earlier periodic table, called the eightfold way. The eightfold way, like the periodic table, enabled prediction of previously undiscovered entities. When the predicted omega-minus particle was found in 1964, the eightfold way was viewed as confirmed.

The eightfold way was developed by Murray Gell-Mann on the basis of abstract mathematics, not on the basis of some physical understanding of why it should work. The same year that the eightfold way was confirmed, Gell-Mann introduced his physical explanation, called the quark model. The quark model explained most particles as combinations of other particles, called quarks, that have fractional charges (omitted from the quark model were electrons, neutrinos, and their relatives). The quark model was even more successful than the eightfold way, although its first confirmed prediction did not occur until 1977.

The strange particles of 1947 also started another major line of thinking. Again, the problem was that some particles decayed in ways that violated prevailing theories. Frank Yang and T.D. Lee concluded that this decay problem could be explained if nature distinguished between right and left in certain instances. A team of experimenters headed by Madame Chien-Shiung Wu showed that the Yang-Lee idea was correct.

The success of Gell-Mann in using a mathematical theory to reach the quark model inspired others to work with similar mathematical ideas—specifically a branch of mathematics called group theory—to explain the particles left out of the quark model. Starting in 1967, this was accomplished to some degree in the electroweak theory, a theory that showed that at high energies two forces that are distinct at the energy levels normally experienced become a single force. The theory was verified by the discovery of predicted new particles in 1983. With that success came many imitators who wanted to use group theory to unify the electroweak force with one of the two remaining forces, called the strong force, into a grand unified theory, or GUT. While promising, the GUTs have remained somewhat unconvincing. Along the way, theorists have turned to other mathematical approaches. The concept of supergravity, which began to be developed in 1976, was combined with such ideas as the following: particles may not be particles but very skinny strings and loops; the universe may not be four dimensional as in Einstein's theories, but 10 or 11 dimensional.

Technology. There are two very different kinds of technology. One is specific to certain problems—for example, Velcro. The other is a generalized new technology that affects many different fields of endeavor—such as the laser. A few technologies are somewhere in between, such as liquid-crystal displays. The period after World War II is particularly rich in all varieties of new technology.

The specific technologies are the ones that perhaps change everyday life the most. Before 1946 cars did not have tubeless or radial-ply tires, power steering or power brakes, or fuel injection, not to mention some of the advanced features available in models today. Remember carbon paper? Now we have copying machines. Think of life without long-playing records, compact discs, or audio or video cassettes; battery-powered watches; microwave ovens; fax documentation; permanent press! These advances change the texture of everyday life.

Besides the laser, two intertwined technologies that started just at the end of the war stand out for the contributions they have made in many fields and the promise of vast changes in the future. These are solid-state electronic devices and digital computers.

The digital computer came first, but would never have been much more than a minor influence on life without the solid-state devices. Early computers with vacuum tubes used too much energy and were "down" most of the time. The transistor, which came along a couple of years after the war, solved both problems. The reliable transistor's descendants made computers cheaper and smaller at an astonishing rate. Today, a thousand dollars will buy a 4 kg (9 lb) computer that has 32 times the memory and speed of computers that cost millions of dollars and filled air-conditioned rooms in the 1940s. Furthermore, the 1940s computer was programmed by hard wiring and its storage memory was a host of magnetic core devices. It was not until 1956 that a computer language was developed; the keyboard for entering data came 11 years later; and it was another three years before data could be stored on floppy disks.

Although the greatest impact of solid-state electronics technology was in computers, solid-state devices, generally called microprocessors, appeared as parts of various other technologies with increasing frequency. The most obvious use has been in miniaturizing radios and television sets. But the ubiquitous microprocessors handle more of an automobile's operation each year. They show up in household appliances as well.

Another new technology that must be mentioned is genetic engineering. Its advances are covered above as biology or medicine. It is not likely, however, that this technology will continue to be limited to those fields (and agriculture). Genetic engineering may someday affect daily life more than solid-state electronics.

New technologies will also continue to change our lives in ways we cannot predict. Somewhere in the mid-1980s, a new Xerox or Velcro or even a new transistor was probably invented. We just don't know about it yet.