EDITOR'S INTRODUCTION: TECHNOLOGY

This volume presents the technology articles from the five-volume reference set *Applied Science*, for the benefit of students considering careers in technology, their teachers, and their counselors. Other volumes cover science and medicine, and engineering and mathematics.

Something should be said at the outset about the relationship between science and technology. Terence Kealey states in his book *The Economic Laws of Scientific Research* (1996) that technology is the activity of manipulating nature, while science is the activity of learning about nature. For much of history, the two realms were relatively separate, technologies being developed by artisans, craftsmen and farmers and the sciences by natural philosophers. Leonard Mlodinow, in *Feynman's Rainbow* (2003) makes a distinction between the Greek way of approaching science and the Babylonian way. The Greeks, the great mathematicians of the ancient world, greatly admired pure thought. The Babylonians, technologists at heart, didn't care much about fine theoretical points but made important practical discoveries. The two realms began coming together at the time of the Industrial Revolution. In England the process was tied to the emergence of the Royal Institution, founded in 1799, which made it possible for the general public to learn about technical matters in their spare time and without the training in classical languages and social standing expected at the universities of Oxford and Cambridge. At about the same time, these august institutions were joined by the "red brick" institutions, which emphasized the training of students for industrial leadership. In the United States, the venerable Ivy League schools, including Harvard, Yale, and Princeton, were joined by the newly established state universities. Some of these were designated as land-grant colleges under the Morrill Act (1862) and were set up to advance agriculture and the mechanical arts. The Morrill Act provided that each state in the Union designate a parcel of land, income from the sale of which would be used to support public colleges and provide for agricultural experimental stations where new ideas in agriculture could be tested.

Educational practice is sometimes slow to recognize changing patterns in society. Colleges in the United States still award bachelor's, master's and doctoral degrees that have their roots in the Middle Ages. In fact the Bachelor of Arts, Master of Arts, and the Doctor of Philosophy degrees are still awarded by the majority of American universities, although the coursework required and the major subjects offered differ greatly from those of a century ago. The bachelor's degree is still awarded to individuals who have completed a four-year course of study, though the emphasis may be on computer science or psycholinguistics instead of the liberal arts. Many schools now award the Bachelor of Science degree to graduates with majors in the sciences (although some, particularly in the Ivy League, award the traditional B.A. degree to all graduates). Additional study is required for the master's degree, and a period of intensive research and the publication of a dissertation is required for the Doctor of Philosophy degree.

Despite the antiquity of the bachelor's, master's and doctoral designations, what the degrees actually meant was, for a time, quite flexible in early-twentieth-century America. Eventually a measure of quality control was achieved, with colleges being chartered by state governments and subject to review by regional accrediting agencies and, in some fields, by additional specialized agencies.

To meet the needs of rapidly growing economy, a number of credentials below that of the bachelor's degree had to be introduced. In modern usage a technologist is someone who has completed a program of study (usually four years in length) and been awarded a bachelor's degree in some field of technology. Technology programs may be distinguished from engineering programs by their mathematics requirement. Programs leading to a bachelor's degree in, say, electrical engineering usually include at least three semesters of calculus and one in differential equations before the Bachelor of Science in Electrical Engineering (B.S.E.E.) is awarded. In contrast, programs leading to a bachelor's degree in electrical engineering technology would require a single introductory course in calculus. In the United States, both types of programs receive accreditation from the American Board for Engineering and Technology (ABET), which is responsible for maintaining standards of instruction in those fields.

Many workers in technology areas do not, in fact, have bachelor's degrees. These workers are generally referred to as technicians rather than technologists. A two-year program in technology at a community college or technical institute could lead to an Associate of Applied Science (A.A.S.) degree. There is also the possibility of various certificates attesting to technical competence, especially in rapidly changing computer-related fields. Further routes toward technical training are provided by the U.S. Armed Forces, and many a technically-trained soldier or sailor moves from a few years of enlistment to a good job in industry. Many large school systems include vocational-technical schools where high school- and college-age students can study such subjects as air-conditioning technology or computer programming.

To the Student

Your decision to enter a technology-based field is one that, with persistence, will lead to a comfortable income and, more importantly, a variety of interesting work assignments. While in junior high and high school, be sure to practice writing and organizing presentations. If possible do not interrupt your study of mathematics, as mathematics courses build on each other. Resist the temptation to take an easy semester. Start or join a technology club at your school. Talk with people who are working in jobs you think you might enjoy. Visit nearby sites that employ technicians or technologists. Learn as much as you can before you commit to a particular career track.

As a technology-minded student, you are likely to be affected by two recent trends. One is the recent growth in on-line education. Although the widespread availability of computers and the Internet make it possible for students almost anywhere to study almost anything, there is still much to be said for the pre-professional socialization that goes on in college. For science majors, needing to keep to a schedule of assignments, working collaboratively with other students, developing presentation skills, and finding information by research are all established aspects of college life. The second trend is the increasing importance of the adult student and the need for continuing education. While there are still individuals who work at the same job for 30 or more years, it is likely that you will change jobs several times over the course of your career, and you can count on needing periodic retraining.

A Brief Survey of Technologies

A clear distinction between science and technology is not possible. As scientific knowledge developed, it was occasionally put into the service of technology, particularly in the nineteenth- and twentieth century. In modern times, advances in scientific knowledge have often stimulated entirely new technologies. When American inventor Thomas Alva Edison sought a long-lasting filament for the first electric light, he proceeded mainly by trial and error. His notebooks report numerous attempts with different filament materials. Edison, however, did proceed with a background knowledge of fundamental science. He understood that most materials, when heated in air, would react with the oxygen to form an oxide, and therefore he focused on filaments carrying current in either a vacuum or an inert atmosphere. In 1883 Edison stumbled on the "Edison effect"—the fact that electric current would flow from a heated metal filament across an evacuated space to a positively charged conductor. Edison recorded the effect in his notebooks, but seeing no application for it, he did not pursue it. In 1897 the English physicist Joseph John Thomson discovered the electron, and it soon became apparent that the Edison effect was simply the emission of electrons from a hot metal surface. By 1904 English physicist John Ambrose Fleming had invented the vacuum-tube diode, and in 1906 the American inventor Lee de Forest showed how incorporating a third electrode would allow a very small voltage to control a much larger current, the effect that made radio and television possible.

At the close of World War II, there was considerable debate as to the proper relationship between science and government in peacetime. Some conservatives wanted to impose strong military control over scientific research. In 1945 Vannevar Bush, who had been director of the wartime Office of Scientific Research and Development, published the report "Science: The Endless Frontier," which painted a very rosy picture of the gains to be derived by public investment in basic scientific research. Among other things, Bush emphasized the role that government could play in supporting research in universities, research to fill in the middle ground between purely academic research and research directed toward immediate objectives. Further, universities had a natural role to play in training the next generation of scientists and engineers. Bush's arguments led to establishment of the National Science Foundation and to expanded research funding within and by the National Institutes of Health in the United States. This trend was accelerated by the Soviet Union's launch of Sputnik 1, the first Earth satellite, in 1957, an event that shook the American public's faith in the inevitable superiority of American technology. In the twenty-first century, science and technology are supported by many sources, public and private, and the pace of development is perhaps even greater than at any time in the past.

The Preliterate World

According to archaeologists and anthropologists, the development of written language occurred relatively recently in human history, perhaps about 3000 B.C.E. Many of the basic components of technology date to those preliterate times, when humans struggled to secure the basic necessities—food, clothing, and shelter—against a background of growing population and changing climate. When food collection was limited to hunting and gathering, knowledge of the seasons and animal behavior was important for survival. The development of primitive stone tools and weapons greatly facilitated both hunting and obtaining meat from animal carcasses, as well as the preservation of the hides for clothing and shelter. Sometime in the middle Stone Age, humans obtained control over fire, making it possible to soften food by cooking and to separate some metals from their ores. Control over fire also made it possible to harden earthenware pottery and keep predatory animals away at night.

With gradually improved living conditions, human fertility and longevity both increased, as did competition for necessities of life. Spoken language, music, magical thinking, and myth developed as a means of coordinating activity. Warfare, along with more peaceful approaches, was adopted as a means of settling disputes, while society was reorganized to ensure access to the necessities of life, including protection from military attack.

The Ancient World

With the invention of written language, it became possible to enlarge and coordinate human activity on an unprecedented scale. Several new areas of technology and engineering were needed. Cities were established so that skilled workers could be freed from direct involvement in food production. Logistics and management became functions of the scribal class, the members of which could read and write. Libraries were built and manuscripts collected. The beginnings of mathematics may be seen in building, surveying, and wealth tabulation. Engineers built roads so that a ruler could oversee his enlarged domain and troops could move rapidly to where they were needed. Taxes were imposed to support the central government, and accounting methods were introduced. Aqueducts were needed to bring fresh water to the cities.

Astronomy, the Calendar, and Longitude

One might think that astronomy could serve as a paradigmatic example of fundamental science, but astronomy—and later space science—provides an example of a scientific activity often pursued for practical benefit. Efforts to fix the calendar, in particular, provide an interesting illustration of the interaction among pure astronomy, practicality and religion.

The calendar provided a scheme of dates for planting and harvesting. Ancient stone monuments in Europe and the Americas may have functioned in part as astronomical observatories, to keep track of the solstices and equinoxes. The calendar also provided a means for keeping religious feasts, such as Easter, in synchrony with celestial events, such as the vernal equinox. Roman emperor Julius Caesar introduced a calendar based on a year of 365 days. This calendar, called the Julian, would endure for more than 1,500 years. Eventually, however, it was realized that the Julian year was about six hours shorter than Earth's orbital period and so was out of sync with astronomical events. In 1583 Pope Gregory XIII introduced the system of leap-year days. The Gregorian calendar is out of sync with Earth's orbit by only one day in 3,300 years.

Modern astronomy begins with the work of Nicolaus Copernicus, Galileo Galilei, and Sir Isaac Newton. Copernicus was the first to advance the heliocentric model of the solar system, suggesting that it would be simpler to view Earth as a planet orbiting a stationary sun. Copernicus, however, was a churchman, and fear of opposition from church leaders (who were theologically invested in an Earth-centered hierarchy of the universe) led him to postpone publication of his ideas until the year of his death. Galileo was the first to use a technological advance, the invention of the telescope, to record numerous observations that called into question the geocentric model of the known universe. Among these was the discovery of four moons that orbit the planet Jupiter.

At the same time, advances in shipbuilding and navigation served to bring the problem of longitude to prominence. Out of sight of land, a sailing ship could easily determine its latitude on a clear night by noting the elevation of the pole star above the horizon. To determine longitude, however, required an accurate measurement of time, which was difficult to do onboard a moving ship at sea. Galileo was quick to propose that occultations by Jupiter of its moons could be used as a universal clock. The longitude problem also drew the attention of the great Isaac Newton. Longitude would eventually be solved by John Harrison's invention of a chronometer that could be used on ship, and the deciphering of it also fostered an improved understanding of celestial mechanics. John Harrison was a carpenter, an early technologist.

Since the launching of the first artificial satellites, astronomy—or, rather, space and planetary science—has assumed an even greater role in applied science. The safety of astronauts working in space requires understanding the dynamics of solar flares. A deeper understanding of the solar atmosphere and its dynamics could also have important consequences for long-range weather prediction.

The Scientific Revolution

The Renaissance and the Protestant Reformation marked something of a rebirth of scientific thinking. This "scientific revolution" would not have been possible without Gutenberg's printing press and the technology of printing with movable type. With wealthy patrons, natural philosophers felt secure in challenging the authority of Aristotle. Galileo published arguments in favor of the Copernican solar system. In the *Novum Organum* (1620; "New Instrument"), Sir Francis Bacon formalized the inductive method, by which generalizations could be made from observations, which then could be tested by further observation or experiment. In England in 1660, with the nominal support of the British Crown, the Royal Society was formed to serve as a forum for the exchange of scientific ideas and the support and publication of research results. Need for larger-scale studies brought craftsmen into the sciences, culminating in the recognition of the professional scientist. Earlier Bacon had proposed that the government undertake the support of scientific investigation for the common good. Bacon himself tried his hand at frozen-food technology. While on a coach trip, he conceived the idea that low temperatures could preserve meat. He stopped the coach, purchased a chicken from a farmer's wife, and stuffed it with snow. Unfortunately he contracted pneumonia while doing this experiment and died forthwith.

The Industrial Revolution followed on the heels of the scientific revolution in England. Key to the Industrial Revolution was the technology of the steam engine, the first portable source of motive power that was not dependent on human or animal muscle. The modern form of the steam engine owes much to James Watt, a self-taught technologist. The steam engine powered factories, ships, and, later, locomotives. In the case of the steam engine, technological advance preceded the development of the pertinent science—thermodynamics and the present-day understanding of heat as a random molecular form of energy.

It is not possible, of course, to do justice to the full scale of applied science and technology in this short space. In the remainder of this introduction, consideration will be given to only a few representative fields, highlighting the evolution of each area and its interconnectedness with fundamental and applied science as a whole.

Chemical Technology

In 1792 the Scottish inventor William Murdock discovered a way to produce illuminating gas by the destructive distillation of coal, producing a cleaner and more dependable source of light than previously was available and bringing about the gaslight era. The production of illuminating gas, however, left behind a nasty residue called coal tar. A search was launched to find an application for this major industrial waste. An early use, the waterproofing of cloth, was discovered by the Scottish chemist Charles Macintosh, resulting in the raincoat that now carries his name. In 1856 English chemist William Henry Perkin discovered the first of the coal-tar dyes, mauve. The color mauve, a deep lavender-lilac purple, had previously been obtained from plant sources and had become something of a fashion fad in Paris by 1857. The fad spread to London in 1858, when Queen Victoria chose to wear a mauve velvet dress to her daughter's wedding. The demand for mauve outstripped the supply of vegetable sources. The discovery of several other dyes followed.

The possibility of dyeing living tissue was rapidly seized on and applied to the tissues of the human body and the microorganisms that afflict it. German bacteriologist Paul Ehrlich proposed that the selective adsorption of dyes could serve as the basis for a chemically based therapy to kill infectious disease-bearing organisms.

Optical Technology, the Microscope and Microbiology

The use of lenses as an aid to vision may date to China in 500 B.C.E. Marco Polo, in his journeys more than 1,700 years later, reported seeing many Chinese wearing eyeglasses. In 1665 English physicist (and curator of experiments for the Royal Society) Robert Hooke published his book *Micrographia* ("Tiny Handwriting"), which included many illustrations of living tissue. Antonie van Leeuwenhoek was influenced by Hooke, and he reported many observations of microbial life to the Royal Society. The simple microscopes of Hooke and van Leeuwenhoek suffered from many forms of aberration or distortion. Subsequent investigators introduced combinations of lenses to reduce the aberrations, and good compound microscopes became available for the study of microscopic life around 1830.

While van Leeuwenhoek had reported the existence of microorganisms, the notion that they might be responsible for disease or agricultural problems met considerable resistance. Louis Pasteur, an accomplished physical chemist, became best known as the father of microbiology. Pasteur was drawn into applied research by problems arising in the fermentation industry. In 1857 he announced that fermentation was the result of microbial action. He also showed that the souring of milk resulted from microorganisms, leading to the development of "pasteurization"—heating to a certain temperature for a specific amount of time— as a technique for preserving milk. As a sequel to his work on fermentation, Pasteur brought into question the commonly held idea that living organisms could generate spontaneously. Through carefully designed experiments, he demonstrated that broth could be maintained sterile indefinitely, even when exposed to the air, provided that bacteria-carrying dust was excluded.

Pasteur's further research included investigating the diseases that plagued the French silk industry. He also developed a means of vaccinating sheep against infection by Bacillus anthracis and a vaccine to protect chickens against cholera. Pasteur's most impressive achievement may have been the development of a treatment effective against the rabies virus for people bitten by rabid dogs or wolves.

Pasteur's scientific achievement illustrates the close interplay of fundamental and applied advances that occurs in many scientific fields. Political scientist Donald Stokes has termed this arena of application-driven scientific research "Pasteur's Quadrant," to distinguish it from purely curiosity-driven research (as in modern particle physics); advance by trial and error (for example, Edison's early work on the electric light); and the simple cataloging of properties and behaviors (as in classical botany and zoology). The study of applied science is a detailed examination of Pasteur's Quadrant.

Electromagnetic Technology

The history of electromagnetic devices provides an excellent example of the complex interplay of fundamental and applied science. The phenomena of static electricity and natural magnetism were described by Thales of Miletus in ancient times, but they remained curiosities through much of history. The magnetic compass was developed by Chinese explorers in about 1100 b.c.e., and the nature of Earth's magnetic field was explored by William Gilbert (physician to Queen Elizabeth I) around 1600. By the late eighteenth century, a number of devices for producing and storing static electricity were being used in popular demonstrations, and the lightning rod, invented by Benjamin Franklin, greatly reduced the damage due to lightning strikes on tall buildings. In 1800 Italian physicist Alessandro Volta developed the first electrical battery. Equipped with a source of continuous electric current, scientists made electrical and electromagnetic discoveries, practical and fundamental, at a breakneck pace.

The voltaic pile, or battery, was employed by British scientist Sir Humphry Davy to isolate a number of chemical elements for the first time. In 1820 Danish physicist Hans Christian Ørsted discovered that any current-carrying wire is surrounded by an electric field. In 1831 English physicist Michael Faraday discovered that a changing magnetic field would induce an electric current in a loop of wire, thus paving the way for the electric generator and the transformer. In Albany, New York, schoolteacher Joseph Henry set his students the challenge of building the strongest possible electromagnet. Henry would move on to become professor of natural philosophy at Princeton University, where he invented a primitive telegraph.

The basic laws of electromagnetism were summarized in 1865 by Scottish physicist James Clerk Maxwell in a set of four differential equations that yielded a number of practical results almost immediately. These equations described the behavior of electric and magnetic fields in different media, including in empty space. In a vacuum it was possible to find wavelike solutions that appeared to move in time at the speed of light, which was immediately realized to be a form of electromagnetic radiation. Further, it turned out that visible light covered only a small frequency range. Applied scientists soon discovered how to transmit messages by radio waves, electromagnetic waves of much lower frequency.

The Computer

One of the most clearly useful of modern artifacts, the digital electronic computer, as it has come to be known, has a lineage that includes the most abstract of mathematics, the automated loom, the vacuum tubes of the early twentieth century, and the modern sciences of semiconductor physics and photochemistry. Although computing devices such as the abacus and slide rule themselves have long histories, the programmable digital computer has advanced computational power by many orders of magnitude. The basic logic of the computer and the computer program, however, arose from a mathematical logician's attempt to answer a problem arising in the foundations of mathematics.

From the time of the ancient Greeks to the end of the nineteenth century, mathematicians had assumed that their subject was essentially a study of the real world, the part amenable to purely deductive reasoning. This included the structure of space and the basic rules of counting, which led to the rules of arithmetic and algebra. With the discovery of non-Euclidean geometries and the paradoxes of set theory, mathematicians felt the need for a closer study of the foundations of mathematics, to make sure that the objects that might exist only in their minds could be studied and talked about without risking inconsistency.

David Hilbert, a professor of mathematics at the University of Göttingen, was the recognized leader of German mathematics. At a mathematics conference in 1928, Hilbert identified three questions about the foundations of mathematics that he hoped would be resolved in short order. The third of these was the so-called decidability problem: Was there was a foolproof procedure to determine whether a mathematical statement was true or false? Essentially, if one had the statement in symbolic form, was there a procedure for manipulating the symbols in such a way that one could determine whether the statement was true in a finite number of steps?

British mathematician Alan Turing presented an analysis of the problem by showing that any sort of mathematical symbol manipulation was in essence a computation and thus a manipulation of symbols not unlike the addition or multiplication one learns in elementary school. Any such symbolic manipulation could be emulated by an abstract machine that worked with a finite set of symbols that would store a simple set of instructions and process a one-dimensional array of symbols, replacing it with a second array of symbols. Turing showed that there was no solution in general to Hilbert's decision problem, but in the process he also showed how to construct a machine (now called a Turing machine) that could execute any possible calculation. The machine would operate on a string of symbols recorded on a tape and would output the result of the same calculation on the same tape. Further, Turing showed the existence of machines that could read instructions given in symbolic form and then perform any desired computation on a one-dimensional array of numbers that followed. The universal Turing machine was a programmable digital computer. The instructions could be read from a one-dimensional tape, a magnetically stored memory, or a card punched with holes, as was used for mechanized weaving of fabric.

The earliest electronic computers were developed at the time of World War II and involved numerous vacuum tubes. Since vacuum tubes are based on thermionic emission—the Edison effect mentioned above—they produced immense amounts of heat and involved the possibility that the heating element in one of the tubes might well burn out during the computation. In fact, it was standard procedure to run a program, one that required proper function of all the vacuum tubes, both before and after the program of interest. If the results of the first and last computations did not vary, one could assume that no tubes had burned out in the meantime.

World War II ended in 1945. In addition to the critical role of computing machines in the design of the first atomic bombs, computational science had played an important role in predicting the behavior of targets. The capabilities of computing machines would grow rapidly following the invention of the transistor by John Bardeen, Walter Brattain and William Shockley in 1947. In this case, fundamental science led to tremendous advances in applied science.

The story of semiconductor science is worth telling. Silicon is unusual in displaying an increase in electrical conductivity as the temperature is raised. In general, when one finds an interesting property of a material, one tries to purify and refine the material. Purified silicon, however, lost most of its conductivity. On further investigation, it was found that tiny concentrations of impurities could vastly change both the amount of electrical conductivity and the mechanism by which it occurs. Because the useful properties of semiconductors depend critically on the impurities, or "dirt," in the material, solid-state (and other) physicists sometimes refer to the field as "dirt physics." Adding a small amount of phosphorus to pure silicon resulted in n-type conductivity, the type due to electrons moving in response to an electric field. Adding an impurity such as boron produced p-type conductivity, in which electron vacancies (in chemical bonds) moved through the material. Creating a p-type region next to an n-type produced a junction that let current flow in one direction and not the other, just as in a vacuum-tube diode. Placing a p-type region between two n-types produced the equivalent of Lee de Forest's diode—a transistor. The transistor, however, did not require a heater and could be miniaturized.

The 1960s saw the production of integrated circuits—many transistors and other circuit elements on a single silicon wafer, or chip. Currently hundreds of thousands of circuit elements are available on a single chip, and anyone who buys a laptop computer will command more computational power than any government could control in 1950.

Donald R. Franceschetti

Further Reading

Bell Telephone Laboratories. A History of Engineering and Science in the Bell System: Electronics Technology, 1925–1975. Ed. by M. D. Fagen. 7 vols. New York: Bell Laboratories, 1975–1985. Provides detailed information on the development of the transistor and the integrated circuit.

Bodanis, David. Electric Universe: How Electricity Switched On the Modern World. New York: Three Rivers Press, 2005. Popular exposition of the applications of electronics and electromagnetism from the time of Joseph Henry to the microprocessor age.

Burke, James. Connections. Boston: Little Brown, 1978; reprint, New York: Simon & Schuster, 2007. Describes linkages among inventions throughout history.

Cobb, Cathy, and Harold Goldwhite. Creations of Fire: Chemistry's Lively History from Alchemy to the Atomic Age. New York: Plenum Press, 1995; reprint, Cambridge, Mass.: Perseus, 2001. History of pure and applied chemistry from the beginning through the late twentieth century.

Garfield, Simon. Mauve: How One Man Invented a Color That Changed the World. New York: W. W. Norton, 2000. Focuses on how the single and partly accidental discovery of coal tar dyes led to several new areas of chemical industry.

Kealey, Terence. The Economic Laws of Scientific Research. New York: St. Martin's Press, 1996. Makes the case that government funding of scientific research is relatively inefficient and emphasizes the role of private investment and hobbyist scientists. Mlodinow, Leonard, Feynman's Rainbow: A Search for Beauty in Physics and in Life. New York: Warner Books, 2003; reprint, New York: Vintage Books, 2011.

Schlager, Neil, ed. Science and Its Times: Understanding the Social Significance of Scientific Discovery. 8 vols. Detroit: Gale Group, 2000–2001. Massive reference work on the impact of scientific and technological developments from the earliest times to the present.

Sobel, Dava. Longitude. New York: Walker & Company, 2007. Story of the competition among scientists and inventors to develop a reliable means of determining longitude at sea.

Stokes, Donald E. Pasteur's Quadrant: Basic Science and Technological Innovation. Washington, D.C.:

Brookings Institution Press, 1997. Presents an extended argument that many fundamental scientific discoveries originate in application-driven research and that the distinction between pure and applied science is not, of itself, very useful.

COMMON UNITS OF MEASURE

Common prefixes for metric units—which may apply in more cases than shown below—include *giga-* (1 billion times the unit), *mega-* (one million times), *kilo-* (1,000 times), *hecto-* (100 times), *deka-* (10 times), *deci-* (0.1 times, or one tenth), *centi-* (0.01, or one hundredth), *milli-* (0.001, or one thousandth), and *micro-* (0.0001, or one millionth).

Unit	***Quantity***	***Symbol***	***Equivalents***
Acre	Area	ac	43,560 square feet 4,840 square yards 0.405 hectare
Ampere	Electric current	A *or* amp	1.00016502722949 international ampere 0.1 biot *or* abampere
Angstrom	Length	Å	0.1 nanometer 0.0000001 millimeter 0.000000004 inch
Astronomical unit	Length	AU	92,955,807 miles 149,597,871 kilometers (mean Earth-Sun distance)
Barn	Area	b	10^{-28} meters squared (approx. cross-sectional area of 1 uranium nucleus)
Barrel (dry, for most produce)	Volume/capacity	bbl	7,056 cubic inches; 105 dry quarts; 3.281 bushels, struck measure
Barrel (liquid)	Volume/capacity	bbl	31 to 42 gallons
British thermal unit	Energy	Btu	1055.05585262 joule
Bushel (U.S., heaped)	Volume/capacity	bsh *or* bu	2,747.715 cubic inches 1.278 bushels, struck measure
Bushel (U.S., struck measure)	Volume/capacity	bsh *or* bu	2,150.42 cubic inches 35.238 liters
Candela	Luminous intensity	cd	1.09 hefner candle
Celsius	Temperature	C	1° centigrade
Centigram	Mass/weight	cg	0.15 grain
Centimeter	Length	cm	0.3937 inch
Centimeter, cubic	Volume/capacity	cm^3	0.061 cubic inch
Centimeter, square	Area	cm^2	0.155 square inch
Coulomb	Electric charge	C	1 ampere second
Cup	Volume/capacity	C	250 milliliters 8 fluid ounces 0.5 liquid pint

L

LASER INTERFEROMETRY

FIELDS OF STUDY

Control engineering; electrical engineering; engineering metrology; interferometry; laser science; manufacturing engineering; materials science; mechanical engineering; nanometrology; optical engineering; optics; physics.

SUMMARY

Laser interferometry includes many different measurement methods that are all based on the unique interference properties of laser lights. These techniques are used to measure distance, velocity, vibration, and surface roughness in industry, military, and scientific research.

KEY TERMS AND CONCEPTS

- **Beam Splitter:** Partially reflecting and partially transmitting mirror.
- **Constructive Interference:** Addition of two or more waves that are in phase, leading to a larger overall wave.
- **Destructive Interference:** Addition of two or more waves that are out of phase, leading to a smaller overall wave.
- **Heterodyne Detection:** Mixing of two different frequencies of light to create a detectable difference in their interference pattern.
- **Homodyne Detection:** Mixing of two beams of light at the same frequency, but different relative phase, to create a detectable difference in their interference pattern.
- **Monochromatic:** Containing a single wavelength.
- **Spatial Coherence:** Measure of the phase of light over a defined space.
- **Temporal Coherence:** Measure of the phase of light as a function of time.

Definition and Basic Principles

Laser interferometry is a technique that is used to make extremely precise difference measurements between two beams of light by measuring their interference pattern. One beam is reflected off a reference surface and the other either reflects from or passes through a surface to be measured. When the beams are recombined, they either add (constructive interference) or subtract (destructive interference) from each other to yield dark and light patterns that can be read by a photosensitive detector. This interference pattern changes as the relative path length changes or if the relative wavelength or frequency of the two beams changes. For instance, the path lengths might vary because one object is moving, yielding a measurement of vibration or velocity. If the path lengths vary because of the roughness of one surface, a "map" of surface smoothness can be recorded. If the two beams travel through different media, then the resulting phase shift of the beams can be used to characterize the media.

Lasers are not required for interferometric measurements, but they are often used because laser light is monochromatic and coherent. It is principally these characteristics that make lasers ideal for interferometric measurements. The resulting interference pattern is stable over time and can be easily measured, and the precision is on the order of the wavelength of the laser light.

Background and History

The interference of light was first demonstrated in the early 1800's by English physicist Thomas Young in his double-slit experiment, in which he showed that two beams of light can interact like waves to produce alternating dark and light bands. Many scientists believed that if light were composed of waves, it would require a medium to travel through, and this medium (termed "ether") had never been detected. In the late 1800's, American physicist Albert Michelson designed an interferometer to measure the effect of the ether on the speed of light. His experiment was considered a failure in that he was not able to provide proof of the existence of the ether. However, the utility of the interferometer for measuring a precise distance was soon exploited. One of Michelson's first uses of his interferometer was to measure the international unit of a meter using a platinum-iridium metal bar, paving the way for modern interferometric methods of measurement. Up until the mid-twentieth century, atomic sources were used in interferometers, but their use for measurement was limited to their coherence length, which was less than a meter. When lasers were first developed in the 1960's, they quickly replaced the spectral line sources used for interferometric measurements because of their long coherence length, and the modern field of laser interferometry was born.

How It Works

The most common interferometer is the Michelson interferometer, in which a laser beam is divided in two by use of a beam splitter. The split beams travel at right angles from each other to different surfaces, where they are reflected back to the beam splitter and redirected into a common path. The interference between the recombined beams is recorded on a photosensitive detector and is directly correlated with the differences in the two paths that the light has traveled.

In the visible region, one of the most commonly available lasers is the helium-neon laser, which produces interference patterns that can be visually observed, but it is also possible to use invisible light lasers, such as those in the X-ray, infrared, or ultraviolet regions. Digital cameras and photodiodes are routinely used to capture interference patterns, and these can be recorded as a function of time to create a movie of an interference pattern that changes with time. Mathematical methods, such as Fourier analysis, are often used to help resolve the wavelength composition of the interference patterns. In heterodyne detection, one of the beams is purposefully phase shifted a small amount relative to the other, and this gives rise to a beat frequency, which can be measured to even higher precision than in standard homodyne detection. Fiber optics can be used to direct the light beams, and these are especially useful to control the environment through which the light travels. In this case, the reflection from the ends of the fiber optics have to be taken into account or used in place of reflecting mirrors. Polarizers and wave-retarding lenses can be inserted in the beam path to control the polarization or the phase of one beam relative to the other.

While Michelson interferometers are typically used to measure distance differences between the two reflecting surfaces, there are many other configurations. Some examples are the Mach-Zehnder and Jamin interferometers, in which two beams are reflected off of identical mirrors but travel through different media. For instance, if one beam travels through a gas, and the other beam travels through vacuum, the beams will be phase shifted relative to the other, causing an interference pattern that can be interpreted to give the index of refraction of the gas. In a Fabry-Perot interferometer, light is directed into a cavity consisting of two highly reflecting surfaces. The light bounces between the surfaces multiple times before exiting to a detector, creating an interference pattern that is much more highly resolved than in a standard Michelson interferometer. Several other types of interferometers are described below in relation to specific applications.

Applications and Products

Measures of Standards and Calibration. Because of the accuracy possible with laser interferometry, it is widely used for calibration of length measurements. The National Institute of Standards and Technology (NIST), for example, offers measurements of gauge blocks and line scales for a fee using a modified Michelson-type interferometer. Many commercial companies also offer measurement services based on laser interferometer technology. Typical services are for precise measurement of mechanical devices, such as bearings, as well as for linear, angular, and flatness calibration of other tools such as calipers, micrometers, and machine tools. Interferometers are also used to measure wavelength, coherence, and spectral purity of other laser systems.

Dimensional Measurements. Many commercial laser interferometers are available for purchase and can be used for measurements of length, distance, and angle. Industries that require noncontact measurements of complex parts use laser interferometers to test whether a part is good or to maintain precise positioning of parts during fabrication. Laser interferometers are widely used for these purposes in the automotive, semiconductor, machine tool, and medical- and scientific-parts industries.

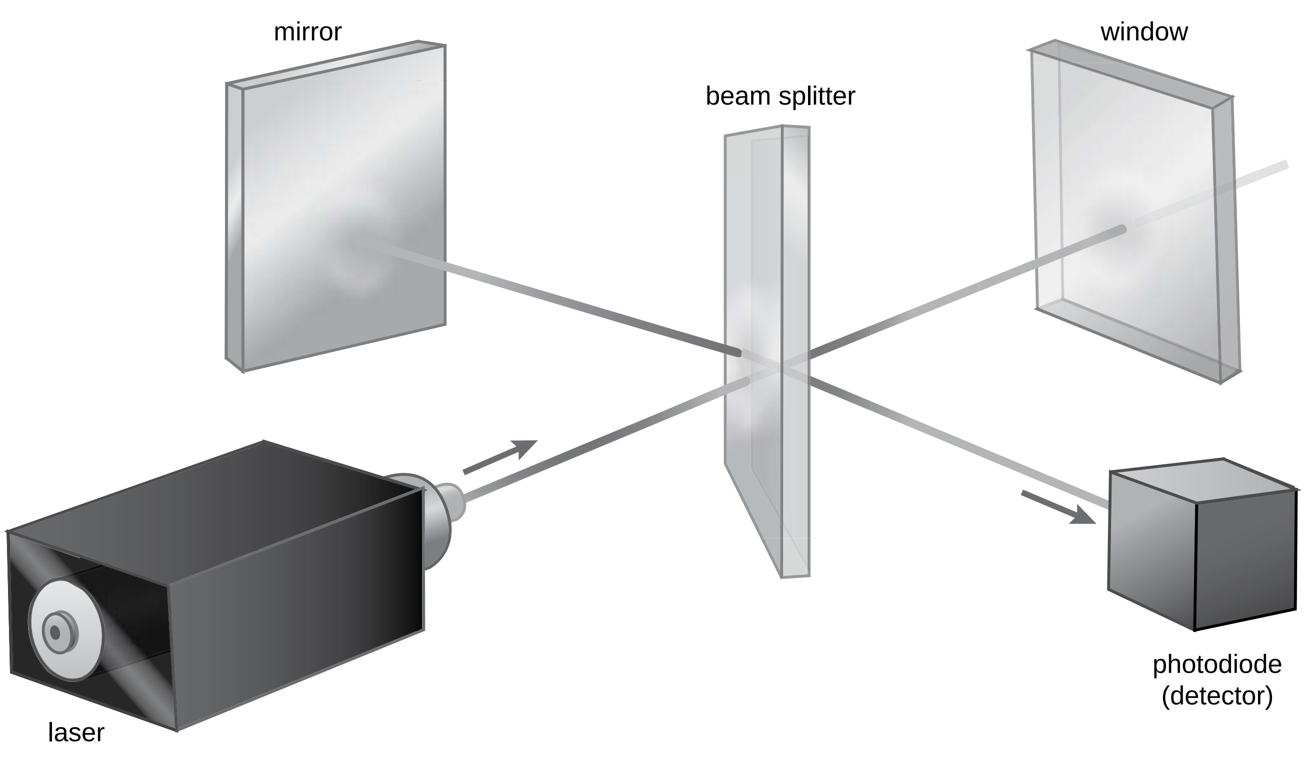
Vibrational Measurements. Laser vibrometers make use of the Doppler shift, which occurs when one laser beam experiences a frequency shift relative to the other because of the motion of the sample. These interferometers are used in many industries to measure vibration of moving parts, such as in airline or automotive parts, or parts under stress, such as those in bridges.

Optical Metrology. Mirrors and lenses used in astronomy require high-quality surfaces. The Twyman-Green and Fizeau interferometers are variations on the Michelson interferometer, in which an optical lens or mirror to be tested is inserted into the path of one of beams, and the measured interference pattern is a result of the optical deviations between the two surfaces. Other industrial optical testing applications include the quality control of lenses in glasses or microscopes, the testing of DVD reader optical components, and the testing of masks used in lithography in the semiconductor industry.

Ring Lasers and Gyroscopes. In the last few decades, laser interferometers have started to replace mechanical gyroscopes in many aircraft navigation systems. In these interferometers, the laser light is reflected off of mirrors such that the two beams travel in opposite directions to each other in a ring, recombining to produce an interference pattern at the starting point. If the entire interferometer is rotated, the path that the light travels in one direction is longer than the path length in the other direction, and this results in the Sagnac effect: an interference pattern that changes with the angular velocity of the apparatus. These ring interferometers are widely available from both civilian and military suppliers such as Honeywell or Northrop Grumman.

Ophthalmology. A laser interferometry technique using infrared light for measuring intraocular

Laser Interferometry



distances (eye length) is widely used in ophthalmology. This technique has been developed and marketed primarily by Zeiss, which sells an instrument called the IOL Master. The technique is also referred to as partial coherence interferometry (PCI) and laser Doppler interferometry (LDI) and is an area of active research for other biological applications.

Sensors. Technology based on fiber-optic acoustic sensors to detect sound waves in water have been developed by the Navy and are commercially available from manufacturers such as Northrop Grumman.

Gravitational Wave Detection. General relativity predicts that large astronomical events, such as black hole formation or supernova, will cause "ripples" of gravitational waves that spread out from their source. Several interferometers have been built to try to measure these tiny disturbances in the local gravitational fields around the earth. These interferometers typically have arm lengths on the order of miles and require a huge engineering effort to achieve the necessary mechanical and vibrational stability of the lasers and the mirrors. There are currently efforts to build space-based gravity-wave-detecting interferometers, which would not be subject to the same seismic instability as Earth-based systems.

Research Applications. Laser interferometers are used in diverse form in many scientific experiments. In many optical physics applications, laser interferometers are used to align mirrors and other experimental components precisely. Interferometers are also used for materials characterization in many basic research applications, while ultrasonic laser interferometers are used to characterize velocity distributions and structures in solids and liquids. A more recent technology development is interferometric sensors, which are used to monitor chemical reactions in real time by comparing laser light directed through waveguides. The interference pattern from the two beams changes as the chemical reaction progresses. This technique is often referred to as dual-polarization interferometry.

Impact on Industry

The invention of the laser in 1960 opened up the field of interferometry to a huge range of applications, allowing measurements both at long distances and with extremely high precision. The following decades saw the initial application of laser interferometry to vibration and dimensional measurements in industrial processes. The invention of cheap semiconductor diode lasers in the last decade has further decreased the price of laser interferometers and has widened the range of accessible wavelengths. Many laser interferometer systems are now available commercially, and they are used in a large segment of the semiconductor, automotive, and measurement industries. Systems now sold by many companies give compact, reliable ways to measure surface roughness, calibrate mechanical components, align or position parts during manufacturing, or for precision machining. Lasers are a multibillion-dollar industry, and laser interferometers are a constantly growing segment of this market.

Laser interferometers have hugely affected the quality control of lenses in the optical-manufacturing industries. Interferometers are the method of choice to measure curvature and smoothness of lenses

Fascinating Facts About Laser Interferometry

- When the first laser was demonstrated in 1960, it was called a "solution looking for a problem."
- The Laser Interferometer Gravitational-Wave Observatory (LIGO) is sensitive to disturbances in the local gravitational fields that are caused by astronomical events as far back in time as 70 million years.
- Sensors based on laser interferometers are being developed to detect acoustic signals for surveillance. A buried sensor can detect the sound of footsteps from as far away as 30 feet.
- The Laser Interferometer Space Antenna (LISA) will consist of three spacecraft orbiting at 5 million kilometers apart and will provide information on the growth and formation of black holes and other events never before seen.
- Laser interferometers will be used to measure the optical quality of the mirror used in the James Webb Space Telescope, scheduled to launch in 2014. The surface smoothness must be unprecedented: If the mirror were scaled up to a size of 3,000 miles across, the surface height would be allowed to vary only by a foot at most.
- Quantum interferometers have been built to recreate the classic double-slit interference experiment, using single atoms instead of a light beam.

used in microscopes, telescopes, and eyeglasses. Companies specializing in optical measurements are available for on- or off-site testing of optical components. Astronomy, in particular, has benefited from the precision testing of polished surfaces made possible by laser interferometers; mirrors such as the ones used in the Hubble Space Telescope would not be possible without a laser interferometry testing system.

The National Science Foundation (NSF) has invested substantially in ground-based interferometers for the measurement of gravity waves to test the predictions of general relativity. In the 1990's, the NSF funded the building of two very large-scale Michelson interferometers in the United States–one in Hanford, Washington, and the other in Livingston, Louisiana. Together they make up the Laser Interferometer Gravitational-Wave Observatory (LIGO) and consist of interferometer arms that are miles long. Though gravity waves have not yet been detected, government-funded efforts around the world continue with large-scale interferometers currently operating in a half-dozen countries.

Sensor technology is a growing field in laser interferometry applications. Sensors based on interference of laser light using fiber optics have been developed to detect environmental changes, such as temperature, moisture, pressure, strain on components, or chemical composition of an environment. These types of sensors are not yet widely commercially available but are in development by industry and by the military for applications such as chemical-agent detection in the field or for use in harsh or normally inaccessible environments. Combined with wireless technology, they could be used, for instance, to monitor environmental conditions far underground or within the walls of buildings.

Careers and Course Work

Basic research on laser interferometry and its applications is conducted in academia, in many metrology industries, and in government laboratories and agencies. For research careers in new and emerging interferometry methods in academia or as a primary investigator in industry, a doctorate degree is generally required. Graduate work should be in the area of physics or engineering. The undergraduate program leading into the graduate program shouldinclude classes in mathematics, engineering, computer, and materials science.

For careers in industries that provide or use commercial laser interferometers but do not conduct basic research, a master's or bachelor's degree would be sufficient, depending on the career path. Senior careers in these industries involve leading a team of engineers in new designs and applications or guiding a new application into the manufacturing field. In this case, the focus of course work should be in engineering. Mechanical, electrical, optical, or laser engineering will provide a solid background and an understanding of the basic theory of interferometer science. Additional courses should include physics, mathematics, and materials science. A bachelor's degree would also be required for a marketing position in laser interferometry industries. In this case, focus should be on business, but a strong background in engineering or physics will make a candidate much more competitive. Technical jobs that do not require a bachelor's degree could involve maintenance, servicing, or calibration of laser interferometers for measurements in industry. They could involve assembly of precision optomechanical systems or machining of precision parts.

Social Context and Future Prospects

The development of increasingly precise interferometers in the last few decades, such as for gravitational-wave measurement, has spurred corresponding leaps in mechanical and materials engineering, since these systems require unprecedented mechanical and vibrational stability. Laser interferometers are beginning to be used in characterization of nanomaterials, and this will push the limits of resolution of laser interferometers even further. As the cost of lasers and optical components continues to decrease, the use of laser interferometers in many industrial manufacturing applications will likely increase. They are an ideal measurement system in that they do not contain moving parts, so there is no wear on parts, and they do not mechanically contact the sample being measured.

Active research is conducted in the field of laser interferometric sensors, with potential applications in military and manufacturing industries. Oil and gas companies may also drive development of sensors for leak and gas detection during drilling. In addition, commercial applications for laser sensors will open up in areas of surveillance as acoustic laser interferometry technology is developed.

Research continues in academic labs in areas that may someday become real-world applications, such as using laser interferometers for the detection of seismic waves, or in the area of quantum interferometry in which single photons are manipulated to interfere with each other in a highly controlled manner.

Corie Ralston, B.S., Ph.D.

Further Reading

Beers, John S., and William B. Penzes. "The NIST Length Scale Interferometer." *Journal of Research of the National Institute of Standards and Technology* 104, no. 3 (May/June, 1999): 225-252. Detailed description of the original NIST Michelson interferometer, with historical context.

Halsey, David, and William Raynor, eds. *Handbook of Interferometers: Research, Technology and Applications.* New York: Nova Science Publishers, 2009. A comprehensive text on current interferometry technologies. Designed for readers with a strong physics background.

Hariharan, P. *Basics of Interferometry*. 2d ed. Burlington, Mass.: Academic Press, 2007. Covers most of the current interferometer configurations and includes sections on applications.

________. *Optical Interferometry*. 2d ed. San Diego: Academic Press, 2003. Overview of the basic theory of interferometry methods, including sections on laser interferometry.

Malacara, Daniel, ed. *Optical Shop Testing*. 3d ed. Hoboken, N.J.: John Wiley & Sons, 2007. An introduction to interferometers used in testing optical components.

Sirohi, Rajpal S. *Optical Methods of Measurement: Wholefield Techniques.* 2d ed. Boca Raton, Fla.: CRC Press, 2009. Covers the basics of wave equations and interference phenomena. Includes multiwavelength techniques of interferometry.

Tolansky, Samuel. *An Introduction to Interferometry*. 2d ed. London: Longman, 1973. Includes many interferometry methods that do not use lasers.

Web Sites

Laser Interferometer Gravitational-Wave Observatory
http://www.ligo.caltech.edu

National Aeronautics and Space Administration
James Webb Space Telescope
http://www.jwst.nasa.gov

National Institute of Standards and Technology
http://www.nist.gov

See also: Laser Technologies

BIOGRAPHICAL DICTIONARY OF SCIENTISTS

Alvarez, Luis W. (1911-1988): A physicist and inventor born in San Francisco, Alvarez was associated with the University of California, Berkeley, for many years. He explored cosmic rays, fusion, and other aspects of nuclear reaction. He invented time-of-flight techniques and conducted research into nuclear magnetic resonance for which he was awarded the 1968 Nobel Prize in Physics. He contributed to radar research and particle accelerators, worked on the Manhattan Project, developed the ground-controlled approach for landing airplanes, and proposed the theory that dinosaurs were rendered extinct by a massive meteor impacting Earth.

Archimedes (c. 287-c. 212 B.C.E.): A Greek born at Syracuse, Sicily, Archimedes is considered a genius of antiquity, with interests in astronomy, physics, engineering, and mathematics. He is credited with the discovery of fluid displacement (Archimedes' principle) and a number of mathematical advancements. He also developed numerous inventions, including the Archimedes screw to lift water for irrigation (still in use), the block-and-tackle pulley system, a practical odometer, a planetarium using differential gearing, and several weapons of war. He was killed during the Roman siege of Syracuse.

Babbage, Charles (1791-1871): An English-born mathematician and mechanical engineer, Babbage designed several machines that were precursors to the modern computer. He developed a difference engine to carry out polynomial functions and calculate astronomical tables mechanically(which was not completed) as well as an analytical engine using punched cards, sequential control, branching and looping, all of which contributed to computer science. He also made advancements in cryptography, devised the cowcatcher to clear obstacles from railway locomotives, and invented an ophthalmoscope.

Bacon, Sir Francis (1561-1626): A philosopher, statesman, author, and scientist born in England, Bacon was a precocious youth who at the age of thirteen began attending Trinity College, Cambridge. Later a member of Parliament, a lawyer, and attorney general, he rejected Aristotelian logic and advocated for inductive reasoning—collecting data, interpreting information, and carrying out experiments—in his major work, *Novum Organum* (*New Instrument*), published in 1620, which greatly influenced science from the seventeenth century onward. A victim of his own research, he experimented with snow as a way to preserve meat, caught a cold that became bronchitis, and died.

Baird, John Logie (1888-1946): A Scottish electrical engineer and inventor, Baird successfully transmitted black-and-white (in 1925) and color (in 1928) moving television images, and the BBC used his transmitters to broadcast television from 1929 to 1937. He had more than 175 patents for such far-ranging and forward-thinking concepts as big-screen and stereo TV sets, pay television, fiber optics, radar, video recording, and thermal socks. Plagued with ill health and a chronic lack of financial backing, Baird was unable to develop his innovative ideas, which others later perfected and profited from.

Bardeen, John (1908-1991): A Wisconsin-born electrical engineer and physicist, Bardeen worked for Gulf Oil, researching magnetism and gravity, and later studied mathematics and physics at Princeton University, where he earned a doctoral degree. While working at Bell Laboratories after World War II he, Walter Brattain (1902-1987), and William Shockley (1910-1989) invented the transistor, for which they shared the 1956 Nobel Prize in Physics. In 1972, Bardeen shared a second Nobel Prize in Physics for a jointly developed theory of superconductivity; he is the only person to win the same award twice.

Barnard, Christiaan (1922-2001): A heart-transplant pioneer born in South Africa, Barnard was a cardiac surgeon and university professor. He performed the first successful human heart transplant in 1967, extending a patient's life by eighteen days, and subsequent transplants—using innovative operational techniques he devised—allowed new heart recipients to survive for more than twenty years. He was one of the first surgeons to employ living tissues and organs from other species to prolong human life and was a contributor to the effective design of artificial heart valves.

Bates, Henry Walter (1825-1892): A self-taught

TIMELINE

The Time Line below lists milestones in the history of applied science: major inventions and their approximate dates of emergence, along with key events in the history of science. The developments appear in boldface, followed by the name or names of the person(s) responsible in parentheses. A brief description of the milestone follows.

2,500,000 B.C.E.	**Stone tools:** Stone tools, used by Homo habilis and perhaps other hominids, first appear in the Lower Paleolithic age (Old Stone Age).
400,000 B.C.E.	**Controlled use of fire:** The earliest controlled use of fire by humans may have been about this time.
200,000 B.C.E.	**Stone tools using the prepared-core technique:** Stone tools made by chipping away flakes from the stones from which they were made appear in the Middle Paleolithic age.
100,000-50,000 B.C.E.	**Widespread use of fire by humans:** Fire is used for heat, light, food preparation, and driving off nocturnal predators. It is later used to fire pottery and smelt metals.
100,000-50,000 B.C.E.	**Language:** At some point, language became abstract, enabling the speaker to discuss intangible concepts such as the future.
16,000 B.C.E.	**Earliest pottery:** The earliest pottery was fired by putting it in a bonfire. Later it was placed in a trench kiln. The earliest ceramic is a female figure from about 29,000 to 25,000 B.C.E., fired in a bonfire.
10,000 B.C.E.	**Domesticated dogs:** Dogs seem to have been domesticated first in East Asia.
10,000 B.C.E.	**Agriculture:** Agriculture allows people to produce more food than is needed by their families, freeing humans from the need to lead nomadic lives and giving them free time to develop astronomy, art, philosophy, and other pursuits.
10,000 B.C.E.	**Archery:** Archery allows human hunters to strike a target from a distance while remaining relatively safe.
10,000 B.C.E.	**Domesticated sheep:** Sheep seem to have been domesticated first in Southwest Asia.
9000 B.C.E.	**Domesticated pigs:** Pigs seem to have been domesticated first in the Near East and in China.
8000 B.C.E.	**Domesticated cows:** Cows seem to have been domesticated first in India, the Middle East, and sub-Saharan Africa.
7500 B.C.E.	**Mud bricks:** Mud-brick buildings appear in desert regions, offering durable shelter. The citadel in Bam, Iran, the largest mud-brick building in the world, was built before 500 B.C.E. and was largely destroyed by an earthquake in 2003.
7500 B.C.E.	**Domesticated cats:** Cats seem to have been domesticated first in the Near East.
6000 B.C.E.	**Domesticated chickens:** Chickens seem to have been domesticated first in India and Southeast Asia.
6000 B.C.E.	**Scratch plow:** The earliest plow, a stick held upright by a frame and pulled through the topsoil by oxen, is in use.
6000 B.C.E.	**Electrum:** The substance is a natural blend of gold and silver and is pale yellow in color like amber. The name "electrum" comes from the Greek word for amber.