EDITOR'S INTRODUCTION: ENGINEERING AND MATHEMATICS

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

Something should be said at the outset about the relationships among science, technology, engineering, and mathematics. 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. To this we may add that engineering is another field devoted to manipulating nature. 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 and engineers at heart, didn't care much about fine theoretical points but made important practical discoveries. Or, in the classical world, a distinction may be drawn between the Greeks and the Romans. The Greeks did beautiful mathematics and built beautiful small temples with roofs supported by many columns. The Romans realized that stone was much stronger under compression than under tension and so used arches to span much larger distances. Thus they could build much larger temples. They also used their arches to build aqueducts to carry water to populous cities.

Technology became far more scientific 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 the 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. This 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 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, although 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 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.

In modern usage an engineer 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 engineering. Many states in the United States provide a route for engineers to be licensed as professional engineers (P.E.s) following college graduation, an apprenticeship period as an Engineer in Training (E.I.T.), and the passing of a rigorous examination. Some engineers regard the P.E. credential as equal to or more desirable than a Ph.D. or Doctor of Engineering (D.Eng.) degree. Engineering programs may be distinguished from technology 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.

Mathematics per se is one of the oldest of human pursuits, having grown out of the building crafts and the need to keep track of one's land, crops, and domestic animals. It reached one peak in classical Greece when the geometry of Euclid seemed to accurately describe the nature of physical space. (That is, the theorems of Euclid seemed to be valid for measured distances.) The Arabs developed algebra somewhat later, while Europe was stuck in the "Dark Ages." Calculus was developed in the seventeenth century, while statics came into its own in the nineteenth century. The twentieth century saw the extensive development of mathematical logic, leading to the design of digital computers. With the invention of the transistor in 1947 and the subsequent development of integrated circuits (computer "chips," which could be manufactured by photolithography), computer technology has grown explosively, while the physical size of computers has shrunk to the point that thousands of transistors can be contained in a cubic inch. Computer science and computer engineering now offer many opportunities for engineers and mathematicians.

To the Student

Your decision to study mathematics or engineering is one that, with persistence, will lead to a comfortable income and, more importantly, a variety of interesting work assignments. While you are in junior high and high school, be sure to practice writing and organizing presentations. If possible do not interrupt your study of mathematics, because mathematics courses build on each other. Do not postpone your first course in physics, on which all engineering is based. Resist the temptation to take an easy semester. In college join the student chapter of a professional society such as the Association for Computing Machinery or the Institute of Electrical and Electronic Engineers. Look for summer work with an engineering firm.

As a future mathematician or engineer, 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 mathematics and engineering students, needing to keep to a schedule of assignments, work collaboratively with other students, develop presentation skills, and find 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 Engineering and Mathematics

Some fields of engineering are of great antiquity. The seven wonders of the ancient world were basically works of civil engineering. The great Archimedes was both engineer and mathematician. The pyramids of Egypt and the aqueducts and roads of the Roman Empire are early examples of civil engineering. The design of fortifications and weapons systems may be taken as an example of military engineering. Mechanical engineering has about as long a history as civil and military engineering, but it really came into its own in the seventeenth century as it became apparent that the physics of Isaac Newton could be applied to mechanical devices. The invention of the steam engine greatly increased the demand for mechanical engineers and precision machinists: the Industrial Revolution in England was largely a consequence of the steam engine, which was first patented by James Watt. With the Watt steam engine as a "prime mover," factories were freed from their dependence on wind and moving water as power sources. Extensive coal mining was undertaken to provide fuel for the new source of mechanical power. Coal and later petroleum led to the fields of chemical and petroleum engineering. Nineteenth-century discoveries about electricity and magnetism would then lead to the field of electrical engineering, which grew explosively in the first half of the twentieth century.

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 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, and 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 Engineering

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 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.

Electrical Engineering

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. Davy also did demonstrations at the Royal Institution involving the effect of electricity on the bodies of recently hanged criminals. (He would later describe these to his friend Mary Shelley who went on to pen the novel *Frankenstein.*) 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 a long history, 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. But vacuum tubes produce 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 commands more computational power than any government could control in 1950.

The computer has put new tools at the disposal of the engineer as well as scholars in other fields. Magnetic and optical methods of storage make it possible to record large amounts of information in a very small space. Storage of several trillion characters is now possible using far less than a cubic inch of space. Computer programs can now search through the millions of test items to find the one that best matches search criteria, in a second or so.

The notion that computers can actually "think" like people is still hotly debated. John McCarthy coined the term Artificial Intelligence in 1955. Since then computers have found new proofs of theorems in Euclidean geometry and have been used to discover trends in experimental data. Artificial Intelligence (AI) programs called "expert systems" have been used to diagnose diseases, devise new chemical syntheses and defeat chess masters at their own game.

Evolutionary computing is another recent development. Instead of trying to find the single best solution to certain types of problems, evolutionary computing forms a population of approximate solutions—sometimes called "chromosomes"—to the problem and then alters the population on the basis of "survival of the fittest," making more replicates of the better solution and discarding some of those solutions that are less fit. The solution process allows several biologically inspired mutations to occur between generations. Eventually a steady state is reached, with the optimum solution in the majority.

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Further Reading

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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

ELECTRONIC MATERIALS PRODUCTION

FIELDS OF STUDY

Mathematics; physics; chemistry; crystallography; quantum theory; thermodynamics

SUMMARY

While the term "electronic materials" commonly refers to the silicon-based materials from which computer chips and integrated circuits are constructed, it technically includes any and all materials upon which the function of electronic devices depends. This includes the plain glass and plastics used to house the devices to the exotic alloys and compounds that make it possible for the devices to function. Production of many of these materials requires not only rigorous methods and specific techniques but also requires the use of high-precision analytical methods to ensure the structure and quality of the devices.

KEY TERMS AND CONCEPTS

- **Biasing:** The application of a voltage to a semiconductor structure (transistor) to induce a directional current flow in the structure.
- **Czochralski Method:** A method of pulling material from a molten mass to produce a single large crystal.
- **Denuded Zone:** Depth and area of a silicon wafer that contains no oxygen precipitates or interstitial oxygen.
- **Epi Reactor:** A thermally programmable chamber in which epitaxial growth of silicon chips is carried out.
- **Gettering:** A method of lowering the potential for precipitation from solution of metal contaminants in silicon, achieved by controlling the locations at which precipitation can occur.
- **Polysilicon (Metallurgical Grade Silicon):** A form of silicon that is 99 percent pure, produced by the reaction of silicon dioxide (SiO_2) and carbon (C) to produce silicon (Si) and carbon monoxide (CO) at a temperature of 2000 degrees Celsius.

Definition and Basic Principles

Electronic materials are those materials used in the construction of electronic devices. The major electronic material today is the silicon wafer, from which computer chips and integrated circuits (ICs) are made. Silicon is one of a class of elements known as semiconductors. These are materials that do not conduct electrical currents appreciably unless acted upon, or "biased," by an external voltage. Another such element is germanium.

The construction of silicon chips requires materials of high purity and consistent internal structure. This, in turn, requires precisely controlled methods in the production of both the materials and the structures for which they are used. Large crystals of ultrapure silicon are grown from molten silicon under strictly controlled environmental conditions. Thin wafers are sliced from the crystals and then polished to achieve the desired thickness and mirror-smooth surface necessary for their purpose. Each wafer is then subjected to a series of up to five hundred, and sometimes more, separate operations by which extremely thin layers of different materials are added in precise patterns to form millions of transistor structures. Modern CPU (central processing unit) chips have between 10^7 and 10^9 separate transistors per square centimeter etched on their surfaces in this way.

One of the materials added by the thin-layer deposition process is silicon, to fill in spaces between other materials in the structures. These layers must be added epitaxially, in a way that maintains the base crystal structure of the silicon wafer.

Other materials used in electronic devices are also formed under strictly controlled environmental conditions. Computers could not function without some of these materials, especially indium tin oxide (ITO) for what are called transparent contacts and indium nitride for light-emitting diodes in a full spectrum range of colors.

Background and History

The production of modern electronic materials began with the invention of the semiconductor bridge transistor in 1947. This invention, in turn, was made possible by the development of quantum theory and the vacuum tube technology with which electronic devices functioned until that time.

The invention of the transistor began the development of electronic devices based on the semiconducting character of the element silicon. Under the influence of an applied voltage, silicon can be induced to conduct an electrical current. This feature allows silicon-based transistors to function somewhat like an on-off switch according to the nature of the applied voltage.

In 1960, the construction of the functional laser by American physicist and Nobel laureate Arthur Schawlow began the next phase in the development of semiconductor electronics, as the assembly of transistors on silicon substrates was still a tedious endeavor that greatly limited the size of transistor structures that could be constructed. As lasers became more powerful and more easily controlled, they were applied to the task of surface etching, an advance that has produced ever smaller transistor structures. This development has required ever more refined methods of producing silicon crystals from which thin wafers can be cut for the production of silicon semiconductor chips, the primary effort of electronic materials production (though by no means the most important).

How It Works

Melting and Crystallization. Chemists have long known how to grow large crystals of specific materials from melts. In this process, a material is heated past its melting point to become liquid. Then, as the molten material is allowed to cool slowly under controlled conditions, the material will solidify in a crystalline form with a highly regular atomic distribution.

Now, molten silicon is produced from a material called polysilicon, which has been stacked in a closed oven. Specific quantities of doping materials such as arsenic, phosphorus, boron, and antimony are added to the mixture, according to the conducting properties desired for the silicon chips that will be produced. The polysilicon melt is rotated in one direction (clockwise); then, a seed crystal of silicon, rotating in the opposite direction (counterclockwise), is introduced. The melt is carefully cooled to a specific temperature as the seed crystal structure is drawn out of the molten mass at a rate that determines the diameter of the resulting crystal.

To maintain the integrity of the single crystal that results, the shape is allowed to taper off into the form of a cone, and the crystal is then allowed to cool completely before further processing. The care with which this procedure is carried out produces a single crystal of the silicon alloy as a uniform cylinder, whose ends vary in diameter first as the desired extraction rate was achieved and then due to the formation of the terminal cone shape.

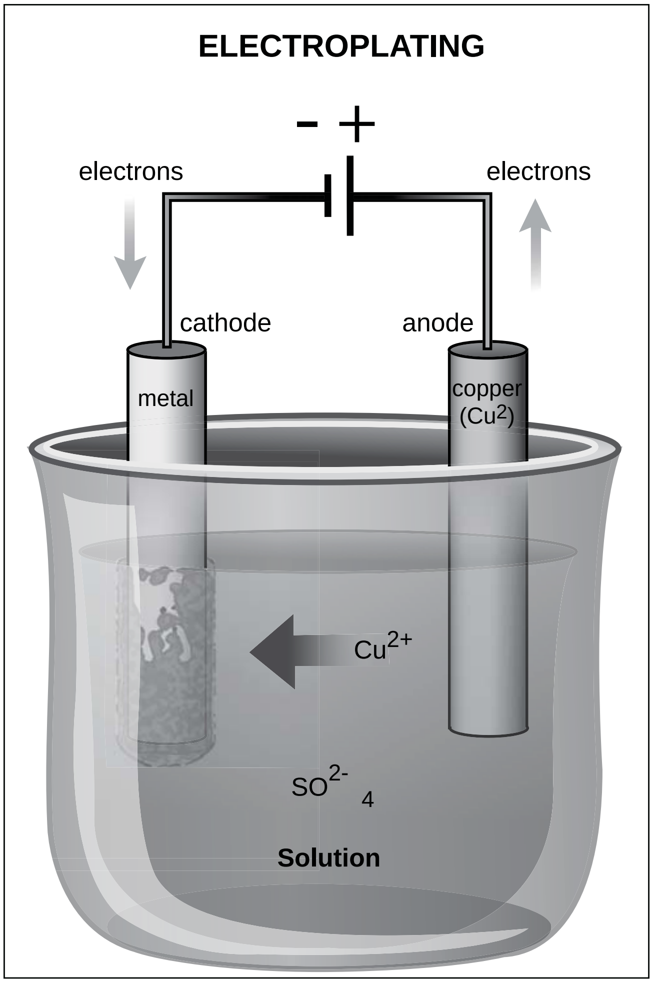
Wafers. In the next stage of production, the nonuniform ends of the crystal are removed using an inner diameter saw. The remaining cylinder of crystal is called an ingot, and is then examined by X ray to determine the consistency and integrity of the crystal structure. The ingot then will normally be cut into smaller sections for processing and quality control.

To produce the rough wafers that will become the substrates for chips, the ingot pieces are mounted on a solid base and fed into a large wire saw. The wire saw uses a single long moving wire to form a thick network of cutting edges. A continuous stream of slurry containing an extremely fine abrasive provides the cutting capability of the wire saw, allowing the production of many rough wafers at one time. The rough wafers are then thoroughly cleaned to remove any residue from the cutting stage.

Another procedure rounds and smooths the edges of each wafer, enhancing its structural strength and resistance to chipping. Each wafer is also laser-etched with identifying data. They then go on to a flat lapping procedure that removes most of the machining marks left by the wire saw, and then to a chemical etching process that eliminates the marking that the lapping process has left. Both the lapping process and the chemical etching stage are used to reduce the thickness of the wafers.

Polishing. Following lapping and rigorous cleaning, the wafers move into an automated chemical-mechanical polishing process that gives each wafer an extremely smooth mirror-like and flat surface. They are then again subjected to a series of rigorous chemical cleaning baths, and are then either packaged for sale to end users or moved directly into the epitaxial enhancement process.

Epitaxial Enhancement. Epitaxial enhancement is used to deposit a layer of ultrapure silicon on the surface of the wafer. This provides a layer with different properties from those of the underlying wafer material, an essential feature for the proper functioning of the MOS (metal-oxide-semiconductor) transistors that are used in modern chips. In this process, polished wafers are placed into a programmable oven and spun in an atmosphere of trichlorosilane gas. Decomposition of the trichlorosilane



Electroplating is the creation of an adherent metal layer on some substrate by electrolysis.

deposits silicon atoms on the surface of the wafers. While this produces an identifiable layer of silicon with different properties, it also maintains the crystal structure of the silicon in the wafer. The epitaxial layer contains no imperfections that may exist in the wafer and that could lead to failure of the chips in use.

From this point on, the wafers are submitted to hundreds more individual processes. These processes build up the transistor structures that form the functional chips of a variety of integrated circuit devices and components that operate on the principles of digital logic.

Applications and Products

Microelectronics. The largest single use of silicon chips is in the microelectronics industry. Every digital device functions through the intermediacy of a silicon chip of some kind. This is as true of the control pad on a household washing machine as it is of the most sophisticated and complex CPU in an ultramodern computer.

Digital devices are controlled through the operation of digital logic circuits constructed of transistors built onto the surface of a silicon chip. The chips can be exceedingly small. In the case of integrated circuit chips, commonly called ICs, only a few transistors may be required to achieve the desired function.

The simplest of these ICs is called an inverter, and a standard inverter IC provides six separate inverter circuits in a dual inline package (DIP) that looks like a small rectangular block of black plastic about 1 centimeter wide, 2 centimeters long, and 0.5 centimeters thick, with fourteen legs, seven on each side. The actual silicon chip contained within the body of the plastic block is approximately 5 millimeters square and no more than 0.5 millimeters thick. Thousands of such chips are cut from a single silicon wafer that has been processed specifically for that application.

Inverters require only a single input lead and a single output lead, and so facilitate six functionalities on the DIP described. However, other devices typically use two input leads to supply one output lead. In those devices, the same DIP structure provides only four functionalities. The transistor structures are correspondingly more complex, but the actual chip size is about the same. Package sizes increase according to the complexity of the actual chip and the number of leads that it requires for its function and application to physical considerations such as dissipation of the heat that the device will generate in operation.

In the case of a modern laptop or desktop computer, the CPU chip package may have two hundred leads on a square package that is approximately 4 centimeters on a side and less than 0.5 centimeters in thickness. The actual chip inside the package is a very thin sheet of silicon about 1 square centimeter in size, but covered with several million transistor structures that have been built up through photo-etching and chemical vapor deposition methods, as described above. Examination of any service listing of silicon chip ICs produced by any particular manufacturer will quickly reveal that a vast number of different ICs and functionalities are available.

Solar Technology. There are several other current uses for silicon wafer technology, and new uses are yet to be realized. Large quantities of electronic-grade silicon wafers are used in the production of functional solar cells, an area of application that is experiencing high growth, as nonrenewable energy resources become more and more expensive. Utilizing the photoelectron effect first described by Albert Einstein in 1905, solar cells convert light energy into an electrical current. Three types are made, utilizing both thick (> 300 micrometers [μm]) and thin (a few μm) layers of silicon. Thick-layer solar cells are constructed from single crystal silicon and from large-grain polycrystalline silicon, while thin-layer solar cells are constructed by using vapor deposition to deposit a layer of silicon onto a glass substrate.

Microelectronic and Mechanical Systems. Silicon chips are also used in the construction of microelectronic and mechanical systems (MEMS). Exceedingly tiny mechanical devices such as gears and single-pixel mirrors can be constructed using the technology developed for the production of silicon chips. Devices produced in this way are by nature highly sensitive and dependable in their operation, and so the majority of MEMS development is for the production of specialized sensors, such as the accelerometers used to initiate the deployment of airbag restraint systems in automobiles. A variety of other products are also available using MEMS technology, including biosensors, the micronozzles of inkjet printer cartridges, microfluidic test devices, microlenses and arrays of microlenses, and microscopic versions of tunable capacitors and resonators.

Other Applications. Other uses of silicon chip technology, some of which is in development, include mirrors for X-ray beams; mirrors and prisms for application in infrared spectroscopy, as silicon is entirely transparent to infrared radiation; and the material called porous silicon, which is made electrochemically from single-crystal silicon and has itself presented an exceptionally varied field of opportunity in materials science.

As mentioned, there are also many other materials that fall into the category of electronic materials. Some, such as copper, gold, and other pure elements, are produced in normal ways and then subjected to methods such as zone refining and vapor deposition techniques to achieve high purity and thin layers in the construction of electronic devices. Many exotic elements and metallic alloys, as well as specialized plastics, have been developed for use in electronic devices. Organic compounds known as liquid crystals, requiring no extraordinary synthetic measures, are normally semisolid materials that have properties of both a liquid and a solid. They are extensively used as the visual medium of thin liquid crystal display (LCD) screens, such as would be found in wristwatches, clocks, calculators, laptop and tablet computers, almost all desktop monitors, and flat-screen televisions.

Another example is the group of compounds made up of indium nitride, gallium nitride, and aluminum nitride. These are used to produce light-emitting diodes (LEDs) that provide light across the full visible spectrum. The ability to grow these LEDs on the same chip now offers a technology that could completely replace existing CRT (cathode ray tube) and LCD technologies for visual displays.

Impact on Industry

Electronic materials production is an entire industry unto itself. While the products of this industry are widely used throughout society, they are not used in the form in which they are produced. Rather, the products of the electronic materials industry become input supplies for further manufacturing processes. Silicon chips, for example, produced by any individual manufacturer, are used for in-house manufacturing or are marketed to other manufacturers, who, in turn, use the chips to produce their own particular products, such as ICs, solar cells, and microdevices.

This intramural or business-to-business market aspect of the electronic materials production industry, with its novel research and development efforts and especially given the extent to which society now relies on information transfer and storage, makes ascribing an overall economic value to the industry impossible. One has only to consider the number of computing devices produced and sold each year around the world to get a sense of the potential value of the electronic materials production industry.

Ancillary industries provide other materials used by the electronic materials production industry, many of which must themselves be classified as electronic materials. An electric materials company, for example, may provide polishing and surfacing materials, photovoltaic materials, specialty glasses, electronic packaging materials, and many others.

Given both the extremely small size and sensitivity of the structures created on the surface of silicon chips and the number of steps required to produce those structures, quality control procedures are stringent. These steps may be treated as part of a multistep synthetic procedure, with each step producing a yield (as the percentage of structures that meet functional requirements). In silicon-chip production, it is important to understand that only the chips that are produced as functional units at the end of the process are marketable. If a process requires two hundred individual construction steps, even a 99 percent success rate for each step translates into a final yield of functional chips of only 0.99^{200}, or 13.4 percent. The majority of chip structures fail during construction, either through damage or through a step failure. It is therefore imperative that each step in the construction of silicon chips be precisely carried out.

To that end, procedures and quality control methods have been developed that are applicable in other situations too. Clean room technology that is essential for maximizing usable chip production is equally valuable in biological research and medical treatment facilities, applied physics laboratories, space exploration, aeronautics repair and maintenance facilities, and any other situations in which steps to protect either the environment or personnel from contamination must be taken.

CAREERS AND COURSEWORK

Electronic materials production is a specialist field that requires interested students to take specialist training in many subject areas. For many such careers, a university degree in solid state physics or electronic engineering is required. For those who will specialize in the more general field of materials science, these subject areas will be included in the overall curriculum. Silicon technology and semiconductors are also primary subject areas. The fields of study listed here are considered prerequisites for specialist study in the field of electronic materials production, and students can expect to continue studies in these subjects as new aspects of the field develop.

Researchers are now looking into the development of transistor structures based on graphene. This represents an entirely new field of study and application, and the technologies that develop from it will also set new requirements for study. High-end spectrometric methodologies are essential tools in the study and development of this field, and students can expect to take advanced study and training in the use of techniques such as scanning probe microscopy.

Fascinating Facts About Electronic Materials Production

- Large single crystals of silicon are grown from a molten state in a process that literally pulls the molten mass out into a cylindrical shape.
- About 70 percent of silicon chips fail during the manufacturing process, leaving only a small percentage of chips that are usable.
- Silicon is invisible to infrared light, making it exceptionally useful for infrared spectroscopy and as mirrors for X rays.
- Quantum dot and graphene-based transistors will produce computers that are orders of magnitude more powerful than those used today.
- The photoelectric effect operating in silicon allows solar cells to convert light energy into an electrical current.
- Semiconductor transistors were invented in 1947 and integrated circuits in 1970, and the complexity of electronic components has increased by about 40 percent each year.
- Copper and other metals dissolve very quickly in liquid silicon, but precipitate out as the molten material cools, often with catastrophic results for the silicon crystal.
- Porous silicon is produced electrochemically from single crystals of silicon. Among its other properties, porous silicon is highly explosive.

SOCIAL CONTEXT AND FUTURE PROSPECTS

Moore's law has successfully predicted the progression of transistor density that can be inscribed onto a silicon chip. There is a finite limit to that density, however, and the existing technology is very near or at that limit. Electronic materials research continues to improve methods and products in an effort to push the Moore limit.

New technologies must be developed to make the use of transistor logic as effective and as economic as possible. To that end, there exists a great deal of research into the application of new materials. Foremost is the development of graphene-based transistors and quantum dot technology, which will drive the level of technology into the molecular and atomic scales.

Richard M. Renneboog, M.Sc.

Further Reading

Akimov, Yuriy A., and Wee Shing Koh. "Design of Plasmonic Nanoparticles for Efficient Subwavelength Trapping in Thin-Film Solar Cells." *Plasmonics* 6 (2010): 155-161. This paper describes how solar cells may be made thinner and lighter by the addition of aluminum nanoparticles on a surface layer of indium tin oxide to enhance light absorption.

Askeland, Donald R. *The Science and Engineering of Materials*. London: Chapman & Hall, 1998. A recommended resource, this book provides a great deal of fundamental background regarding the physical behavior of a wide variety of materials and processes that are relevant to electronic materials production.

Falster, Robert. "Gettering in Silicon: Fundamentals and Recent Advances." *Semiconductor Fabtech* 13 (2001). This article provides a thorough description of the effects of metal contamination in silicon and the process of gettering to avoid the damage that results from such contamination.

Zhang, Q., et al. "A Two-Wafer Approach for Integration of Optical MEMS and Photonics on Silicon Substrate." *IEEE Photonics Technology Letters* 22 (2010): 269-271. This paper examines how photonic and micro-electromechanical systems on two different silicon chips can be precisely aligned.

Zheng, Y., et al. "Graphene Field Effect Transistors with Ferroelectric Gating." *Physical Review Letters* 105 (2010). This paper discusses the experimental development and successful testing of a graphene-based field-effect transistor system using gold and graphene electrodes with SiO_2 gate structures on a silicon substrate.

Web Sites

SCP Symposium (June 2005) "Silicon Starting Materials for Sub-65nm Technology Nodes."
http://www.memc.com/assets/file/technology/papers/SCP-Symposium-Seacrist.pdf

University of Kiel "Electronic Materials Course."
http://www.tf.uni-kiel.de/matwis/amat/elmat_en/index.html

See also: Applied Physics; Computer Engineering; Computer Science; Electronics and Electronic Engineering; Integrated-Circuit Design.

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

GLOSSARY

absolute zero: The complete absence of thermal energy, resulting in a temperature of -273.15 degrees Celsius. This temperature is the basis for the Kelvin scale (starting at 0 Kelvin) developed by the British physicist, Lord Kelvin, in 1848. What living organisms feel as heat or warmth is a difference in temperature between two objects, which results in a transfer of thermal energy. Molecules at absolute zero have no thermal energy to transfer but can receive thermal energy from contact with a warmer object. *See also* cold, heat, temperature.

acid: A compound containing hydrogen ions (with a positive charge) in its molecules, which are released when the acid is dissolved in water. Acids include such familiar hazardous substances as sulphuric, nitric, and hydrochloric acid, essential nutrients such as ascorbic acid (vitamin C), and common flavorings or preservatives such as acetic or ethanoic acid (vinegar). Acids react chemically with substances known as bases. The balance of acids and bases in a solution is measured by the pH scale, from 0 (strongly acidic) to 7 (neutral) to 14 (strongly alkaline). *See also* alkali, basic chemical.

alkali: A base that is dissolved in water. Alkaline substances are identified by a measurement from 8 to 14 on the pH scale. *See also* basic chemical.

alpha particle: One of three common forms of radiation from the nuclei of unstable radioactive elements, consisting of two protons and two neutrons, identical to the nucleus of a helium atom, without its electron shell. It has a velocity in air of one-twentieth the speed of light. *See also* beta particle, gamma ray.

amino acids: Biological molecules that serve as the building blocks of proteins and enzymes. Amino acids are incorporated into proteins by transfer RNA, according to the genetic code contained in DNA. The majority of amino acids have names ending with -ine, and are complex arrangements of atoms of carbon, nitrogen, hydrogen, and oxygen. *See also* enzyme, protein.

animal husbandry: The art and science of breeding, raising, and caring for domesticated animals, primarily in small- or large-scale agriculture, as sources of food, leather, wool, and other products useful to humans. Husbandry skills are not only required for many jobs in agriculture but for zookeepers, maintaining rodent and amphibian populations in laboratories, and for large-scale veterinary and animal-vaccination practices.

antiseptic: Any chemical substance that kills or inhibits the growth of microorganisms causing sepsis—putrefaction, decay, or other infection—generally applied to surface tissues of human or other living organisms or to nonliving surfaces that may harbor microorganisms.

atmosphere: The layers of gas surrounding the solid or liquid surfaces of a planet. The atmosphere of the Earth is 78.08 percent nitrogen, 20.95 percent oxygen, less than one percent argon, and hundredths or thousandths of a percent neon, helium, and hydrogen. The amounts of water vapor, carbon dioxide, methane, nitrous oxide, and ozone vary with biological (and more recently industrial) processes. Water can rise to as high as four percent. The atmosphere has been divided by different studies into five to six distinct layers: the troposphere, tropopause, stratosphere, mesosphere, and ionosphere (or thermosphere), plus the very thin exosphere fading into interplanetary space. The ozone layer is in the upper level of the stratosphere.

atom: The smallest particle of matter that has the characteristics of an element, such as oxygen, iron, calcium, or uranium. Three subatomic particles are common to all atoms: protons, neutrons, and electrons. The characteristics of any atom are determined by the number of these particles, particularly the negatively charged electrons in the outer shell. *See also* compound, element, molecule, periodic table of the elements.

atomic number: The number of protons (positively charged particles) in the nucleus of an atom, also the number of electrons (negative charge) in the atom in its standard form. Ions of an atom have larger or smaller levels of electron charge. *See also* electron, ion, periodic table of the elements, proton.

atomic weight: The total mass of the protons and neutrons in an atomic nucleus, with a tiny addition for the weight of electrons. Uranium has the

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.