EDITOR'S INTRODUCTION

It has been traditional to describe areas of scientific endeavor as either fundamental or applied. Work in the fundamental areas is said to be curiosity driven, while work in the applied areas is motivated by human needs, or at least the desire to bring a more appealing product to market. It is not, however, possible to draw a rigid dividing line between fundamental and applied science. Knowledge of no identifiable value today may be urgently needed for application tomorrow. Take the chemistry of uranium compounds as an example. Once an obscure academic backwater, the chemistry of uranium compounds became a national concern during World War II, when it was realized that a new class of weapons based on uranium fission could be developed. Similarly, the essential genetic material, deoxyribonucleic acid (DNA), was identified in 1868, but its role in genetics was not suspected for decades and its applications to genetic engineering and DNA fingerprinting not for another century. On the other hand, advances in applied science such as the ability to produce a good vacuum, which was needed for electron tubes and used in the first computers, radio, and television, were also essential to the discovery of the electron and the development of the particle accelerators used to gain a better understanding of the forces of nature. This introductory essay presents an overview of the history of applied science and its interplay with the development of fundamental scientific knowledge and the larger culture.

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. Technology has been a feature of human culture since the Stone Age, when humans first learned to fabricate tools. At first, technology was advanced by trial and error. As scientific knowledge developed, it was occasionally put into the service of technology, particularly in the nineteenth and twentieth centuries. A clear distinction between science and technology is not possible either. 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. However, Edison did proceed with a background 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. 1n 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, 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.

Common Themes

As we consider the evolution of pure and fundamental science, a number of recurrent themes can be noted. One is the growth of the human population. With improvements in agriculture and medical knowledge, the human population increased, resulting in a competition for scarce resources and a greater coordination of human activities. At times, warfare resulted, with many scientific advances coming from military necessity. The science of physics has been valued particularly for providing an understanding of projectiles, ranging from rocks to arrows to cannonballs to ballistic missiles. In the middle of the twentieth century, the science of computing proved of great military value as an aid in locating the enemy, cracking its codes, and designing the most advanced weapon systems.

A second theme concerns the increasing investment that has been made in scientific research and development. To the ancient Greeks, scientific thinking was a luxury proper to the leisure class. The notion of systematic scientific research, to be done by a skilled professional class paid for its scientific work and involving possibly lengthy investigation, and the development of instruments such as the telescope, the microscope, and the voltaic pile, had to wait for the scientific revolution of the seventeenth century. At first, scientists sought patrons among the wealthy and the nobility, much as composers or painters did. Later, corporations would be formed to exploit scientific discoveries. Corporate investment was stimulated by the development of patent law, which gave inventors salable rights to their inventions for a limited time in exchange for public disclosure of how they worked. When large fortunes began to be amassed by families, such as the Rockefellers and the Du Ponts, the introduction of an inheritance tax, and later the income tax, led to the creation of great foundations to support medical and astronomical research. A further change in the scale and organization of scientific research would occur when in 1942 the United States government committed itself to the Manhattan Project, the development of a weapon of unprecedented power.

At the close of World War II, there was considerable debate as to the proper relation 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. Bush's arguments led to establishment of the National Science Foundation and 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 third theme is the ultimate interconnectedness of the different branches of science and technology. This will be particularly important for anyone preparing for a career in science or technology. It is no longer wise to concentrate on just one field of endeavor, such as solid-state physics or computer engineering. One never knows when one's one field will be revolutionized by developments originating in another. One must keep an eye on technology as a whole.

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 applied science 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 and also 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 applied science and engineering were needed. Cities were established so that skilled workers could be freed from direct involvement in food production. Logistics and management become functions of the scribe class, which could read and write. Libraries were built and manuscripts collected. The beginnings of mathematics can be seen in building, surveying, and tabulating wealth. Engineers built roads so that a ruler could oversee the 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.

The applied science of materials became critical at this juncture. Clay could be made into bricks under the tropic sun, and the biblical book of Exodus describes the use of straw fibers to increase tensile strength. While terra-cotta vessels continued to be made, kilns could reach high enough temperatures to produce glazed vessels. Bronze became the material of choice both for weapons and heavy-duty pottery.

About 500 b.c.e., the ancient Greeks begin speculating on why substances behave as they do. Empedocles advanced the theory that all matter is composed of four elements: air, earth, fire, and water. This basic theory was embraced by the great medical thinker Hippocrates in his humoral theory of disease. Democritus and his teacher Leucippus argued that matter is composed of indestructible atoms. Plato proposed that the atoms were shaped like the regular solids and added a fifth substance, or quintessence, to account for heavenly bodies. His student Aristotle accepted the four-element theory but rejected the existence of atoms. Aristotle would hold great sway over medieval thinkers, and the existence of atoms, now assumed by all scientists, would remain in doubt until the beginning of the twentieth century. One can only speculate on whether acceptance of the atomic theory (which could explain, for example, why alloys such as bronze were stronger than the metals of which they were composed) would have made for a much more rapid advance of technology.

While the Babylonians and Egyptians proved themselves as master builders, the science of building proceeded largely by trial and error. Centuries before Euclid, these societies discovered the 3:4:5 right triangle and used it to prepare right angles where needed in building. The Greeks excelled at deductive logic and developed the notion of mathematical proof. Ironically, though, Greek thinkers thought that the terrestrial world was too imperfect to be described by mathematics and so missed the opportunity to develop physics along modern lines.

The So-Called Dark Ages and the Commercial Revolution

In 313 b.c.e., the Roman emperor Constantine converted to Christianity. While this meant better living conditions for the growing Christian population, it also meant the destruction of the products of pagan culture. The famous library at Alexandria was burned in 391 on the orders of the emperor. The fall of the Roman Empire and the destruction of the library at Alexandria in the third century b.c.e. marked a decline in learning that would continue for more than five hundred years. At the same time, Christianity, which had become the official religion of the empire with the conversion of the emperor, emphasized the world to come over the present one. Nonetheless, progress in technology continued, new agricultural techniques were introduced, and the horse became a potent contributor to both warfare and agriculture. Scientific ideas eventually made their way back into European culture.

The Crusades of 1095 to 1291 made Europeans more aware of the larger world and of the possibilities provided by trade with the Middle East and Far East. Trade required the development of durable forms of money and a system of banking to finance expeditions that could be lost or could return great profits. Notions of risk had to be quantified and a reliable system of bookkeeping introduced. The leaders in this undertaking were the republics of the Italian peninsula and the Dutch republic. With accumulations of capital, inventors could obtain financing to market their inventions and the notion of a patent—the grant of a legal monopoly to an inventor for a limited time—developed. The first patent appears to have been awarded by the Republic of Florence in 1421 to the architect Filippo Brunelleschi. Provisions for the granting of patents were written into the Statute of Monopolies in England in 1623 and into Article 1 of the United States Constitution of 1787.

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. Fixing the calendar, in particular, provides an interesting illustration of the interaction between 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 fifteen hundred 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 thirty-three hundred 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 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 orbited 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.

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.

Scientific Revolution

The Renaissance and the Protestant Reformation marked something of a rebirth of scientific thinking. 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* (*New Instrument*), Sir Francis Bacon formalized the inductive method, in which generalizations could be made from observations, which then could be tested by further observation or experiment. 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. Bacon also proposed that the government undertake the support of scientific investigation for the common good. Bacon himself tried his hand at applied science. He conceived the idea that low temperatures could preserve meat while on a coach trip. 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, which was the first portable source of motive power not dependent on human or animal muscle. 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 present-day understanding of heat as a random molecular form of energy.

To do justice to the full scale of applied science would indeed take a multivolume encyclopedia such as this one. In the remainder of this introduction, consideration will be made of only a few representative fields, highlighting the evolution of each area and its interconnectedness with fundamental and applied science as a whole.

Applied Chemistry

In 1792, 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 available and bringing about the gaslight era. The production of illuminating gas 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 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 purple, had been obtained from plant sources and had become something of a fashion fad in Paris in 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, and 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.

Optics, 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 seventeen hundred years later, reported seeing many Chinese wearing eyeglasses. English physicist (and curator of experiments for the Royal Society) Robert Hooke published his book *Micrographia* (*Tiny Handwriting*) in 1665, which included many illustrations of living tissue. Antoni van Leeuwenhoek was influenced by Hooke and reported many observations of microbial life to the Royal Society. The simple microscopes of Hooke and Leeuwenhoek suffered from many forms of aberration or distortion. Subsequent investigators introduced combinations of lenses to reduce the aberration, and good compound microscopes became available for the study of microscopic life around 1830.

An accomplished physical chemist, Louis Pasteur is best known as the father of microbiology. Pasteur's work on microbes began with the study of the problems of the fermentation industry. While Leeuwenhoek had reported the existence of microorganisms, the notion that they might be responsible for disease or agricultural problems met considerable resistance.

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 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 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 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 occur in many scientific fields. Political scientist Donald Stokes has termed this arena of application-driven scientific research as 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 but 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, electrical and electromagnetic discoveries, practical and fundamental, accumulated 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 was 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 be 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. For free space, these equations had wavelike solutions that traveled at the speed of light, which was immediately seen 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. However, the basic logic of the computer and the computer program 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 lead 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 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 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 mean time.

World War II ended in 1945. In addition to the critical role computing machines played in the design of the first atomic bombs, computational science 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 was unusual in displaying an increase in electrical conductivity as the temperature was raised. In general, when one finds an interesting property of a material, one tries to purify and refine the material. However, purified silicon 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.

In the 1960's, the production of integrated circuits—many transistors and other circuit elements on a single silicon wafer or chip—began. 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

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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

AGRONOMY

FIELDS OF STUDY

Biology; chemistry; earth science; biotechnology; mineralogy; ecology; field crop production; soil management; horticulture; meteorology; climatology; entomology; plant physiology; plant genetics; turf science.

SUMMARY

Agronomy is the interdisciplinary field in which plant and soil sciences are applied to the production of crops. Agronomists develop ways in which crop yields can be increased and their quality improved. Some agronomists specialize in soil management and land use, which seeks to protect existing farmland and reclaim land for future use in growing crops. Other specialties cover areas such as weed and pest management, meteorology, and the impact of climate change on crop production. The growing importance of biofuels such as ethanol has increased interest in agronomy as a scientific and professional field.

KEY TERMS AND CONCEPTS

- **Biomass:** Plant or animal matter, particularly when used as an energy source.
- **Crop:** Plant product grown for use as food, animal feed, fiber, or fuel.
- **Forage:** Crop category that includes grasses and is used primarily for feeding animals.
- **Herbicide:** Product that kills or controls weeds and other plants that reduce crop yields.
- **Input:** Product added to soil to increase or improve crop yield, such as fertilizer.
- **Irrigation:** Watering of fields to supplement rainfall.
- **Rotation:** System under which the types of crops grown in a field are changed from one season to the next to improve yields.
- **Yield:** Amount of a crop produced within a defined geographic area, such as a field, during one growing season.

Definition and Basic Principles

Agronomy is the study of plants grown as crops for food, animal feed, and nonfood uses such as energy. In the United States, these crops include wheat, corn, soybeans, grasses, cotton, and a wide variety of fruits and vegetables. Leading crops in other countries vary widely, depending on the nature of the local soil, geography, and growing season.

Plant science is a major component of agronomy. Many agronomists look for ways to grow stronger, hardier plants with higher yields. New types of plants are bred by agronomists to contain specific improvements, such as increased nutrient levels or resistance to pests, over earlier breeds. An area of strong interest is the development of plant types that require fewer inputs such as fertilizers and insecticides to perform well.

The field of agronomy also covers the many factors in the environment that play a role in whether a crop succeeds or fails. The chemical makeup and water balance within a crop's soil are leading factors. Weather and climate patterns, both within a single season and over many years, affect the quantity and quality of crop yields. Technology and economics influence demand for certain types of crops, which in turn pushes market prices up and down. Agronomists help producers respond to these factors.

Background and History

Agronomy is nearly as old as human civilization. According to archaeological findings, people have been growing plants for food for more than 10,000 years, starting in the western Asian regions of what was Mesopotamia and the Levant.

Many historians believe that plant cultivation, the earliest form of farming, led to a major change in human culture. The growing season required people to live in one place for long periods of time. Permanent settlements near fields most likely evolved into some of the first villages. These settlements were often near water sources such as rivers, which were needed to irrigate field crops. Some of the first developments in agronomy involved the design and building of water-delivery systems.

The industrial revolution brought widespread change to the field of agronomy. Steam-powered farming equipment replaced draft animals such as horses and mules. Plant scientists developed and standardized new breeds of field crops, which increased yields. By the mid-twentieth century, nearly all corn grown in the United States was from hybrid stock.

The use of inputs such as fertilizers and pesticides also increased, but in some cases caused significant environmental harm. Since the 1990's, agronomists have focused more closely on ways to improve crops without damaging local ecosystems.

How It Works

Field crops require the right plant type and breed, healthy soil, adequate water and nutrients, appropriate growing temperatures and rainfall, and the control of disease and pests in order to succeed.

Plant Breeding and Genetics. When choosing a type of field crop to plant, farmers and growers consider factors such as the hardiness of certain breeds and their expected yields at the end of the harvest season. Buyers of agricultural products such as food-manufacturing companies look for products that are high in quality and contain specific nutritional or chemical properties. Agronomists who specialize in plant breeding and genetics support the needs of both farms and buyers.

Multiple methods are used to create hybrid plants. Some hybrid strains are created by planting one breed next to another and allowing the two breeds to cross-pollinate. Plant scientists also use in vitro techniques, in which plant tissues are combined in a laboratory setting to create strains that would not occur in nature. One technique that has received significant media attention is genetic modification. Genetically modified plants contain genes introduced directly from other sources that create changes in the plant much more quickly than could be generated through traditional breeding.

Soil Health. To support a crop with the highest possible yields, the soil in which the seeds are planted must be in good condition and must match the needs of the particular plant breed. The health of soil can be measured on the basis of its physical properties, its chemical makeup, and the biological material it contains. These qualities are tracked by soil surveys that are conducted and published regularly. Many farmers switch the types of crops they grow in a particular field every few years in order to keep certain soil nutrients from being depleted. This practice is known as crop rotation.

Hydration and Irrigation. Field crops require vast amounts of water. When sources such as rainfall do not provide enough water for healthy plant growth, hydration must be supplemented by irrigation systems. These systems are often based on networks of pipes or hoses connected to sprinklers or drip mechanisms that can supply water to an entire field.

A USDA soil researcher checks ground porosity and collects samples. (Richard T. Nowitz/Photo Researchers, Inc.)

Weather and Climate. Even when a hardy breed of plant is grown in healthy soil and receives enough water, an entire crop can be damaged or destroyed by unexpected weather patterns. Many farmers and growers protect themselves against weather-related risks by purchasing crop insurance, which covers losses in situations such as storms or early freezes. While climate has less variance for individual farmers on a season-by-season basis, changes in climate over the long term can affect the types of plants that grow successfully in a given area. In some cases, climate change can increase or decrease the amount of land suited for growing crops.

Pathology and Pest Control. Like any living organism, field crops are susceptible to natural threats such as disease, predators, and competition from other plants. Agronomists specializing in plant pathology look for ways to fight disease through direct treatment as well as the breeding of new, hardier strains for future crops. Pests such as insects are controlled through the application of inputs such as insecticides. Pest control also influences plant genetics, as in the case of cotton bred to contain a natural compound toxic to boll weevils. Weeds are managed through a combination of herbicides, adjustments to soil properties such as adding or removing water, and the development of plant breeds resistant to weeds.

Applications and Products

Agronomic crops can be broken down into categories in a number of different ways, such as plant type or climate in which the crop is most likely to be found. One of the most common ways in which field crops are grouped is by the end use of the raw material. Nearly all crops in the world can be considered a form of food, animal feed, fiber, energy, or tools for environmental preservation. Some major crops such as corn can be classified in multiple ways, as corn is used for feeding both people and animals and is also refined into ethanol.

Food. Food represents one of the most diverse categories of agronomic crops in the United States and worldwide. When people think of field crops and food, the types of plants that come to mind first are grains such as corn, wheat, and rice. When measured by acres of land planted, grains make up the largest share of agronomic crops grown throughout the world. This category also includes fruits, tree nuts, vegetables, plants grown to be refined into sugar and sweeteners (such as beets and sugarcane), and plants from which oil is made (such as soybeans). While tobacco is not considered a food product, tobacco crops are often included in this category because cigarettes and other items made from tobacco leaves can be consumed only once.

The demand for food crops worldwide grows only as fast as the global population. Individual types of food crops may face sharp increases and drops in demand, however. These changes are influenced by factors such as weather patterns and crop failures, prices set by the commodities markets (which, in turn, make the prices of consumer items rise and fall), and the changing tastes of food buyers. The spike in popular interest in low-carbohydrate diets in the late 1990's had an impact on crops used to make products such as flours and sugars. Similarly, populations in developing countries where incomes are rising often change their food-buying habits and choose items more prominent in North American and European diets than in local ones. This pattern can push up prices for crops such as corn and lower demand for locally grown fruits and vegetables. Interestingly, this trend also works in reverse. Consumers in affluent economies such as the United States have become more interested in buying produce from crops grown locally in an effort to reduce the overall impact on the environment. These kinds of changes can lead to rapid shifts in demand for individual types of agronomic crops.

Animal Feed. As with food, the category of agronomic crops grown for animal feed is dominated by grains. In the United States, the leading feed grains tracked by the U.S. Department of Agriculture (USDA) are corn, sorghum, barley, and oats. Corn makes up the largest share of this category by volume. The USDA estimates that the 2010-2011 growing season will yield a total of nearly 12.5 billion bushels of corn, much of which will be used for animal feed. The combined yield for sorghum, barley, and oats is estimated at less than 1 billion bushels.

A second type of animal-feed crop is hay. Much of the hay grown and harvested in the United States comes from alfalfa plants or a mixture of grass types. Demand for hay is influenced in part by the weather. Farmers feed more hay to their livestock—particularly cattle—in drier conditions. Hay is often grouped by the USDA with a type of crop known as silage. Silage is not a unique plant, but rather the plant stalks and leaves left after the harvesting and processing of grains such as corn and sorghum. Hay and silage together belong to a category of crops known as forage. While forage was once defined as plant matter eaten by livestock grazing in fields, it has been expanded to include plants that are cut, dried, and brought to the animals.

Fiber. Plants grown for nonfood use often fall into the category of fiber. Fiber crops are processed for use in making cloth, rope, paper and packaging, and composite materials such as insulation for homes. In the United States, most of the yearly agronomic fiber crop is made up of cotton plants. The United States is the third-largest grower of cotton in the world. Other plants in this category are jute, sisal, and flax. Jute and sisal are frequently used to make rope, burlap, and rugs. Flax is refined into linen and used in a wide variety of applications ranging from fine clothing and home-decorating products to high-grade papers. Flax fiber is also used in making rope and burlap.

Energy and Environmental Preservation. Most of the agronomic crops in these categories also appear in one of the three categories above. Of the crops grown in the United States as sources of bioenergy, corn tops the list as a source of ethanol. Ethanol sources in other countries include crops such as sugarcane and grasses. Vegetable-based oils made from soybeans are blended into diesel fuel to make a composite known as biodiesel. The refining processes for turning crops into bioenergy sources are not yet as cost-effective as traditional sources of fuel such as petroleum and coal, but this situation is likely to change as technologies improve.

Environmental preservation from the standpoint of agronomic crops is a broad and developing category. It includes the strategic planting and rotating of crops to return depleted nutrients to the soil. It also includes the growth of plants near fields to minimize soil runoff and to protect endangered areas such as wetlands.

Impact on Industry

Government agencies, academic institutions, and the private sector all play an important role in the field of agronomy. Funding from government sources provides much of the financial support needed for technological development. Agencies also lead many of the research initiatives, which are supplemented by the work of scholars at colleges and universities. Private corporations help to spread innovation from one country to another and devote a portion of their profits to research.

Government Agencies. Nearly every country in the world has a national-level government department or agency devoted to agriculture. The departments frequently oversee agencies at the state or local level. The missions of these departments and agencies are to manage each country's agricultural policies and to ensure that public funding is spent on projects that improve the performance of the farming sector. Information on the country's agricultural practices and yields is gathered, published, and used to support policy decisions. The USDA is one of the largest agencies of this type in the world, employing a significant number of agronomists. The USDA also holds regulatory powers over farms and agricultural businesses by setting standards and ensuring that approved practices are followed.

Academic Institutions. A significant amount of the research and development conducted in agronomy takes place at colleges and universities. Academic institutions offer advanced programs of study in subfields of agricultural science such as crop science, environmental management and land use, and soil science. In the United States, state universities established as land-grant institutions are required to fund departments in agricultural science. Many of the members of professional associations such as the American Society of Agronomy and the European Society for Agronomy are faculty members at academic institutions.

Corporations and the Private Sector. Because agriculture is a part of every country's economy, the business of agronomy is one of the most global in scope of any industry. Some of the largest private-sector corporations in the world, such as Cargill, Monsanto and ADM, are focused on agricultural science. These firms develop new seed hybrids to meet goals such as higher yields per growing season and greater resistance to pests such as insects and weeds. Private-sector firms also design and manufacture soil inputs and manage the processing and shipping of raw materials from crops.

Because many of the largest firms in this industry have operations throughout the world, they are well positioned to spread new technological developments quickly from one region to another. However, these firms also receive negative attention from the media and from consumers because of concerns about issues such as the environmental impact of new technologies. The development of genetically modified plants has been a topic of heightened interest in modern times, as the plants do not occur in nature and their long-term environmental effects are not fully documented. Other advances have been less controversial. These include the creation of new crop breeds that require fewer inputs or offer a higher concentration of nutrients such as vitamins, minerals, and proteins.

Careers and Course Work

A career in agronomy requires a solid background in agricultural science. Most agronomists hold bachelor's degrees, while many specialists—particularly those in research or teaching positions—have master's degrees or doctorates. All state colleges and universities established as land-grant institutions offer programs in agronomy or agricultural science as part of their educational mission. These programs allow students to specialize in fields such as plant genetics and breeding, soil science, meteorology and climatology, and agronomic finance and business management.

Students majoring in agronomy take courses in a wide variety of areas. Common fields are mathematics (particularly calculus and geometry), physics, and

Fascinating Facts About Agronomy

- The Weed Science Society of America tracks nearly 3,500 types of weeds in its database. Many have colorful names such as kangaroo thorn and sneezewort yarrow.
- Some historians say that people in the first farming villages appeared not only to tend field crops but also to brew beer and other alcoholic beverages.
- More food is going straight from the farm to the fork. From 1997 to 2007, the amount of food sold by farmers directly to consumers more than doubled, helped by farmers' markets and community-supported agriculture (CSA) programs.
- One of the leading sources of sweeteners in U.S. food products is corn. One bushel of corn provides enough syrup to sweeten more than 400 cans of soda.
- A combine, one of the most common types of farm equipment in the United States, can harvest enough wheat in nine seconds to make seventy loaves of bread.
- Soybeans are used in many nonfood products. Soy-based wax is used to make crayons, which have brighter colors and are easier to use than those made from petroleum-based wax.
- The top three growers of fiber crops in the world are China, India, and the United States. Cotton makes up the largest share in all three countries. In the United States, more than half of all cotton goes into clothing production, which is led by jeans.

mechanics. Depending on the field a student pursues, advanced course work in biology, botany and plant science, and organic chemistry may be needed. Many courses are highly focused in scope, such as plant pathology or the physical properties of soil.

Demand for professionals with agronomy degrees is rising, according to the U.S. Department of Labor. Job growth in the field of agricultural and food science is projected to be 16 percent between 2008 and 2018. The need for reliable, efficient, environmentally sound sources of plant-based food is a major factor. The increasing use of biomass as an energy source is also contributing to the need for agronomists with an up-to-date knowledge of science and technology.

Many agronomists work for companies that serve farms. These companies manufacture inputs such as fertilizers, create new breeds of field crops, and process raw materials such as grains and fibers. Other agronomists work for government agencies, primarily within the USDA, or teach and conduct research at colleges and universities. An estimated 12 percent of agricultural scientists are independent consultants.

Social Context and Future Prospects

One of the turning points in public consciousness about agronomy was the release of Rachel Carson's book *Silent Spring* in 1962. Carson's book linked a number of ecological problems, particularly the deaths of wild plants and birds, to the widespread use of pesticides such as DDT. Many of these pesticides were used on field crops. The book led to the United States ban on DDT in 1972 and increased public awareness of the potential environmental harm in certain farming practices.

Consumer interest in the quality of food sources has been on the rise since the 1990's. While there has been demand for products such as organic foods for much of the twentieth century, the category has grown most quickly at the beginning of the twenty-first century. Some consumers participate in community-supported agriculture (CSA) programs in which fruits, vegetables, dairy, and other items are delivered directly from local farmers. Gourmet and chain restaurants are more likely to advertise their use of locally grown and environmentally sound food ingredients. This demand extends to nonfood items ranging from organic cotton fibers in clothing and linens to plant-based, biodegradable home products. It has also influenced the growth of plant-based, nonpetroleum energy sources such as ethanol.

Agronomists are well positioned to benefit professionally from these trends. Upcoming issues of interest for agronomists are likely to include the impact of changing weather and climate patterns and the ways in which crop yields can be increased without causing environmental harm.

Julia A. Rosenthal, B.A.

Further Reading

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Reed, Matthew. *Rebels for the Soil: The Rise of the Global Organic Food and Farming Movement*. London: Earthscan, 2010. An extensively researched history of organic farming and its political implications.

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Web Sites

Agricultural Council of America
http://www.agday.org/index.php

American Society of Agronomy
http://www.agronomy.org

Crop Science Society of America
http://www.crops.org

Soil Science Society of America
https://www.soils.org

United States Department of Agriculture
http://www.usda.gov

Weed Science Society of America
http://www.wssa.net

See also: Agricultural Science; Climatology; Erosion Control; Food Science; Genetically Modified Food Production; Horticulture; Meteorology; Soil Science.