Hellemans, The Timetables of Science (New York; Simon & Schuster, 1988)

OVERVIEW - Part 1

Greek and Hellenistic science

Science that presents an organized view of the universe developed with the rise of the Greek civilization. The Greeks developed institutions such as the Academy, the Lyceum, and the Museum; these institutions carried on scientific research in somewhat the way that universities do today. When the Academy and Lyceum were closed in 529 AD, and the Museum was destroyed at about the same time, the Greek era in the history of science was over, although Greek writings continued to have great influence for another thousand years or more.

Greek ways and the origin of science

The origins of the people that made up the Greek civilization in antiquity are still not known. It is generally believed that waves of warriors came from the north or from western Asia and invaded Greece around 1400 BC. They soon developed into a seafaring and trading people, and it was perhaps that aspect that predestined them to be the first to practice science in the form we know it today. Navigation was important, and from it the Greeks developed a keen awareness of space and a sense of geometry. It was especially those Greeks who spoke the Ionian dialect and settled on the coast of Asia Minor who were responsible for the birth of science.

Around the sixth century BC, the first Ionian philosophers, Thales, Anaximander, and Anaximenes, started speculating about nature. Although Greek science may have been a continuation of ideas and practices developed by the Egyptians and Babylonians, the Greeks were the first to look for general principles beyond observations. Science before the Greeks, as practiced in Babylonia and Egypt, consisted mainly of the collection of observations and recipes for practical applications.

Speculative philosophy was the new element in Greek thinking. The Greeks detached themselves from observations and tried to formulate general theories that would explain the universe. The Greek philosopher's search for understanding was not inspired by religion or practical application; it was based entirely on the wish to know and to understand. The Greeks were the first to introduce a scientific method, although it was based on reasoning and observation, not on systematic experimentation. (Several Greek scholars performed experiments; for example, Pythagoras is said to have experimented with strings, investigating changes in pitch for various lengths. Empedocles is claimed to have proved that air is material by immersing a tube that is closed at one end.)

There are several reasons why science first developed in Greece and why rational thinking was maintained in that country. First, the Greeks colonized other countries where they encountered myths that were different from their own for the explanation of natural phenomena, thus holding their own beliefs and myths up to question. Second, although popular religion was widespread, the Greeks did not have a strongly organized priesthood or monolithic religious hierarchy. Science, which in Babylonia and Egypt was mainly in the hands of priests, became in Greece a lay movement. The Greeks felt masters of their fate, unlike those who believed in the fatalism of Chaldean astrology. The Greeks were a seafaring people with a decentralized economy who lived in city-states that were largely controlled by upper-class citizens. This led to freedom of expression and thought; philosophical ideas could be discussed freely.

A theory of creation was absent in Greek religion. Science, in a way, played the role of religion in providing theories on the origins of phenomena. However, clashes between established religion and the natural philosophers occurred during the fifth century BC, when the irreligious attitude of the philosophers became an issue. It resulted in the condemnation of Anaxagoras, who had to leave Athens in exile, the death of Socrates, and even attacks on Aristotle.

Growth and decline of Greek science

Greek culture and scientific thinking first developed on the Ionian coast of Asia Minor and then moved to the Aegean isles and the Greek colonies in southern Italy. Early Ionian science was materialistic. The atomists, such as Leucippus and Democritus, believed reality to be em-

600 B.C.-A.D. 529

bodied by matter. The Pythagoreans viewed the universe differently; to them it was to be found in form and number. Pythagorean ideas strongly influenced the school of Plato, and scientific thinking became more metaphysical in nature.

Around the fourth century BC, Athens became the center of Greek intellectual activity. Aristotle, who lived in Athens, where he led the Lyceum, was the most important scholar in Greek antiquity. He was also the first true philosopher of science, introducing the inductive-deductive method, a "scientific method" that still plays a role in scientific thinking today. Aristotle argued that the investigator of nature should deduce general principles from observations—the inductive phase—and then explain the observations by deducing them from the general principles—the deductive phase.

Aristotle was the tutor of Alexander the Great, who conquered the world from Greece to India before his death in 323 BC. Alexander's armies spread the Greek, or Hellenic, culture, producing a fusion that we now call Hellenistic. Hellenistic science was particularly strong in Egypt, especially in the city of Alexandria. Hellenistic mathematicians advanced the study of curved figures and algebra considerably, while Hellenistic astronomers developed a complex view of the universe that produced accurate observational results.

From 146 BC on, although the Greek traditions persisted, most of the Mediterranean, including Greece itself, was dominated by Rome, although Egypt was independent for another couple of centuries. While Roman rule did not explicitly attack science, science did not thrive under it either. Much of the Hellenistic science after the period of Roman domination began took place in Egypt. After the third century AD, however, Hellenistic science fell into further decline, and thereafter little that was new was produced. When most of the Hellenistic world became part of the Byzantine Empire in 395 AD, the situation became, if anything, worse.

The First Scientists

Scientific thinking originated in Greece with the Ionian philosophers Thales, Anaximander, and Anaximenes. All three of them were born in Miletus, a city-state on the coast of Turkey. Although the Egyptian Imhotep might be claimed as a scientist, the Ionian philosophers were the first to believe that people could understand the universe using reason alone rather than mythology and religion. They searched for a prime cause for all natural phenomena. No personal forces of gods were involved, only impersonal, natural processes.

Thales of Miletus (about 600 BC) is regarded as the founder of the Ionian school of natural philosophy. He probably studied in Egypt, where he was exposed to new ideas. It is likely that there he learned the craft of land surveying, from which he deduced geometry. In Mesopotamia he studied astronomy, and it is believed that he predicted a solar eclipse, a feat that gained him a great reputation in Miletus.

Thales searched for a unifying principle or essence underlying all phenomena and identified this essence as water. Matter appeared to him to exist in three forms: mist, water, and earth. He considered mist and earth as forms of water. In the field of astronomy, which he had learned from the Babylonians, Thales claimed that the substance of stars is water.

Anaximander was a pupil of Thales c 610-545 BC; he is believed to have written the earliest scientific book, now lost. His basic principle, the *apeiron*, can be compared with the concept of "ether" of the nineteenth century (*see* "Does the ether exist," p 366). Anaximander also formulated a theory of the origin and evolution of life. He believed that life originated in the sea from the "moist element," which was evaporated by the sun. The presence of shells and marine fossils was for him the proof that the sea covered much of Earth's surface. He postulated that humans must have originated in the sea and have resembled fish.

Anaximenes (c 570-500 BC), who may have been a pupil of Anaximander, is known for his opinion that the rainbow is a natural phenomenon rather than a divine one. He believed that air is the basic principle of the universe.

The rise of the Christian Church also played an important part in the decline of science. The teachings of the Church were unfavorable toward empirical knowledge for several reasons. During the first Christian millenium, many thought that the world was to come to an end very soon, an attitude hardly encouraging investigation of how the universe might work. Early Christian theology had also absorbed many of the ideas of Plato and Aristotle. Although the works of the Greek scholars were not known directly until after the first millenium, many Greek ideas had been passed on to the Christians through Alexandria, where many of the early church fathers lived. The metaphysical and idealistic (in the philosophical meaning of the word) Platonic view of the world, verging on mysticism and leaving little place for actual observation or experimentation, became a mode of thought imposed by Christian theology. Also the Christian outlook on life itself discouraged secular knowledge since it was believed that such knowledge would not help in a life after death. St. Augustine's teaching that all natural processes had a spiritual purpose strongly influenced this view of nature. Symbols and allegories were used to explain natural phenomena. Secular knowledge and science became associated with heathenism, an idea that lead to the destruction of the Library of the Temple of Serapis in Alexandria in 390 by Bishop Theophilus and the murder of the mathematician Hypatia, instigated in 415 by St. Cyril, Bishop of Alexandria.

A note on dates

Dates in Greek and Hellenistic times were not kept rigorously. For one thing, most dates were given in terms of Olympiads; however, to say that an event occurred during the 19th Olympiad only localized it to within a four-year period. Historians have worked out approximate dates for the lives of many of the noted philosophers and scientists of the time from scraps of evidence. Thus, you may read in some sources that Thales was born in 624 BC and died in 546 BC, but neither date has a definite source. Instead, historians know the year that Thales is said to have predicted an eclipse, which astronomical calculations put at 585 BC. When only one date in a person's life is known, it is the custom of historians to assume that the person must have been around 40 when the event occurred, so it is assumed that Thales may have been born around 624 BC. There is a tradition that he lived to be 70, so he may have died in 546 BC.

Given the uncertainty that applies to most dates of this period (Chinese dates of the time are somewhat more certain), we have listed events by decade. Even events for which no specific dates are given did not necessarily occur in the decade listed, but sometime near that decade. In particular, events listed during the first decade of a century may be known only to the century, and often even the century is uncertain.

Major advances

Astronomy. Unlike the Babylonians, who believed that celestial bodies were gods, the Greeks tried to find physical explanations for the celestial phenomena they observed. Because the Greeks considered celestial phenomena to be emanations or evaporations from Earth, early Greek astronomy was not distinguishable from meteorology.

Astronomy occupied a less central position in Greek culture than in Babylonia. The Greeks were less practical and their early astronomical observations were less accurate than those of the Mesopotamian astronomers; however, later Hellenic astronomers improved on Mesopotamian work. The lack of interest in accurate observations was reflected in the state of disarray of the calendar: every Greek city kept time differently.

The main interest of the early Greeks was cosmology, and Greek astronomers came up with a multitude of cosmological models. Thales assumed Earth to be floating in water. Anaximander believed that Earth was a circular disk suspended freely in space; he explained the daily motion of the stars by assuming that they were attached to a sphere that rotated around Earth. The Pythagoreans believed that Earth rotated around a central "fire" that they did not identify with the sun. Parmenides of Elea and Pythagoras of Samos believed Earth to be spherical. Later thinkers, such as Aristotle, believed Earth to be the center of the universe. Aristarchus of Samos challenged this idea and proposed that the sun is at the center of the universe, with Earth and the planets circling around it. Aristarchus' idea was not generally accepted, and Aristotle's geocentric universe, adopted by the Alexandrian astronomer Ptolemy, remained unchallenged until the Renaissance.

Unlike the early Greek astronomers, however, Hellenistic astronomers, such as Eratosthenes, Hipparchus, and Ptolemy, were keen observers. They were able to calculate correctly the size of Earth and the distance to the moon, as well as the positions that the planets would occupy at any given time. The system of planetary motions developed by Hipparchus and refined by Ptolemy became the dominant astronomical work for over a thousand years, until it was replaced by the system of Copernicus, Kepler, and Newton.

Life science. Aristotle is considered the father of the life sciences. Alexander the Great became his patron, funded his work, and arranged for Aristotle to receive samples of plants and animals from all corners of the Alexandrian empire. Aristotle undertook the classification of animals and plants on a large scale. He divided animals into those with and without blood systems, and divided those of the first group into fish, amphibians, reptiles, birds, and mammals. Aristotle believed strongly in a progressive design in the different forms of organisms, an early form of the idea of the Great Chain of Being. He classified organisms into a hierarchy ranging from the most imperfect (plants)

Three Classic Problems

In 430 BC a great plague struck Athens, killing the Athenian leader Pericles in 429. The Athenians appealed to the oracle at Delos to provide a remedy. The oracle said that Apollo was angry because his cubical altar was too small. If it were doubled, the plague would end. The Athenians had a new altar built that was twice the original in length, breadth, and height. The plague became worse. Consulting the oracle again, the Athenians learned that Apollo was angrier than ever. The god wanted the volume of the cube doubled, and the Athenians had octupled it. The plague went on until 423. The problem of doubling the cube went on until the nineteenth century.

Or so the story goes. There are other stories (but not so good) about how the Delian problem, as doubling the cube came to be known, arose. Whatever its origin, the Delian problem together with the problems of squaring the circle and trisecting the angle became the three classic unsolved problems of Greek mathematics.

It is essential to understand that the method of solution for the classic problems was restricted. A solution would count only if it were accomplished by a geometric construction using an unmarked straightedge and a compass that collapsed when it was lifted from the paper. Tradition has it that Plato is responsible for setting this requirement. Although a great many other problems were easily solved under the restriction, the three classics stubbornly refused to yield.

It is likely that the first classic problem was squaring the circle. It is thought that Anaxagoras worked on solving it, about 450 BC, while he was in prison for having claimed that the sun is a giant red-hot stone and that the moon shines by its reflected light. The problem specifically was to construct a square that has the same area as a given circle.

The trisection problem also arose around the same time. In that case, the problem was to find an angle whose angle measure is exactly one third that of a given arbitrary angle. Trisection appears deceptively simple since among the easiest constructions are the trisection of a line and the bisection of an angle. Like the other classic problems, it stumped the ancient Greeks, but not completely.

The apparent progress toward squaring the circle by Hippocrates of Chios (not to be confused with Hippocrates of Cos, the father of medicine) around 430 probably encouraged other mathematicians to continue. Hippocrates succeeded in squaring a region bounded by two arcs of circles. This region looks like a crescent moon and is therefore called a lune. This was the first successful attempt to convert an area bounded by curves to one bounded by straight lines.

A number of mathematicians decided to stretch the rules and solve the problem ignoring Plato's restriction. Hippias of Elis is supposed to have found two different ways to square the circle, both explicitly rejected by Plato (according to Plutarch). One of the methods attributed to Hippias, based on the first curve other than the circle that was well defined and constructible, was used to square the circle at a later date. Similarly, while trying to solve the Delian problem, Menaechmus seems to have discovered the conic sections—the ellipse, the parabola, and the hyperbola. Use of these curves enabled him to duplicate the cube. Archimedes solved two of the classic problems, trisection of the angle and squaring the circle, with his famous Archimedian spiral (a curve invented by Conon of Alexandria). Archimedes also discovered that all that is needed to trisect an angle is a marked straightedge instead of an unmarked one. In a related development, Archimedes managed to square a region bounded by a parabola and a line.

Around 320 AD, Pappus declared that it was impossible to solve any of the classic problems under the Platonic restriction, although he did not offer a proof of this assertion. Nevertheless, many continued to work on the classic problems in the traditional manner. Finally, the nineteenth century produced the definitive "solutions" to all three problems. Each problem was shown to be incapable of any solution that met the Platonic requirement, just as Pappus had stated. In 1837, Pierre Wantzel supplied a rigorous proof that an angle cannot be trisected with an unmarked straightedge and collapsing compass. In 1882, Ferdinand Lindemann showed that π, the ratio of the circumference of a circle to its diameter, is a transcendental number, implying that the circle cannot be squared (*see* "The value of π," p 360). As for the Delian problem, it had been shown even earlier that it required construction of a line whose length is the cube root of two. With a straightedge and compass, it is only possible to construct square roots.

Although it is clear to mathematicians that the solution of the classic problems under Plato's restriction is impossible, amateurs continue to offer their "proofs" of success.

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to the most perfect (man). He studied over 540 species and compared the anatomy of 48 species by dissecting them.

Of great importance was Aristotle's work in embryology. He observed and described the development of embryos and was the founder of comparative embryology. His main discovery in embryology was that the contribution of the mother is as important as that of the father in procreation. Before Aristotle, the common Greek notion was that man supplied the seed that grew into the new individual and that the role of woman in relation to the seed was similar to the role of the soil in relation to the seed of a plant.

Theophrastus, the successor of Aristotle at the Lyceum, continued Aristotle's method of observation and classification by applying it to plants. He described and classified a large number of plants, and coined numerous terms in botany.

Many of the Greek philosophers, including Anaxagoras, Empedocles, Democritus, and Philolaus were physicians or were interested in medicine. Alcmaeon is considered by many the founder of medicine; he knew that the brain is the central controlling organ of the body. He also discovered the optical nerve. Hippocrates of Cos became the best known physician, but during his time several medical schools already existed in Greece and its colonies.

Maps of the world

In Homer's time, the map of the world showed the continental mass formed by parts of Asia, Africa, and Europe surrounded by a vast body of water, Oceanus. Herodotus, however, felt that the Homeric world had too much water and not enough land. To balance things out, he replaced Oceanus with a great desert.

Symmetry was an overriding concern of the Greeks. For example, they noted that a line drawn between the Nile and the Danube would give a somewhat symmetrical version of the known world. But they obtained even more symmetry by carrying Pythagorean ideas over; that is, that Earth must be a sphere. Plato accepted this on purely geometrical grounds, but Aristotle offered a variety of proofs of sphericity from observation. Later Greek geographers accepted the spherical Earth as a matter of course and worked from there.

The Greek belief in symmetry resulted in the accidental insight that there must be a great continent in the Southern Hemisphere. Since the Greeks knew there was a great land mass in the Northern Hemisphere, they believed it must be balanced by one to the south. This tradition, supposedly originating with Ptolemy, allowed considerable freedom in execution for the mapmakers. Pomponius Mela, writing about 43 AD, made Ceylon the northern tip of *terra australis nondum cognita* (the undiscovered southern continent), as the great continent came to be known. By the fifteenth century, maps showed that Terra Australis had attached itself to southern Africa, effectively barring ships from reaching the East by sailing around Africa. When Bartolomeu Dias rounded the Cape of Good Hope in 1487, however, Terra Australis began to shrink.

Some maps from early in the sixteenth century, notably a Turkish map from 1513 and the Orantes Pinnaeus world map of 1532, show Antarctica of about the right size and location. Even the bays and mountain ranges are close to where they are now known to be. Some people think that these are copied from truly ancient maps prepared by a seafaring people who had sailed the globe. It is more probable that among the many versions of Terra Australis, these came closest to the truth.

Another persistent tradition is that some maps before the time of Columbus and Magellan correctly located the Americas. The Portuguese are supposed to have seen a map in Java when they first reached the island that showed South America. The Vinland map, originally dated as 1430 AD, showed North America. Although it was thought to be a fake soon after its discovery, later research suggests that it may be a copy of a real Viking map.

The discovery of the north coast of Australia by Europeans (it may have been known to the Chinese as early as the thirteenth century) would seem to have justified the belief in a giant southern continent, but in the mid-seventeenth century, Abel Tasman circumnavigated Australia, shrinking the polar continent once again. Even in the eighteenth century, however, people continued to believe in the existence of the continent at the South Pole, arguing from the same premise of symmetry as had the Greeks. Alexander Dalrymple was the particular champion of the "Great Southern Continent," but he was passed over on the British government's expedition to find it. Instead, the expedition was put under the leadership of Captain James Cook. While the official purpose of Cook's voyage was to observe the transit of Venus from Tahiti, he also had secret orders to find the Great Southern Continent.

Cook's first voyage located New Zealand, but by circumnavigation showed that it was not the missing continent. In 1772 he started out again, this time with location of the continent as his major goal. Cook reached within 75 miles of Antarctica, but failed to find land. He concluded that the Great Southern Continent was either a myth or so close to the pole as to be beyond navigation. Finally, in the nineteenth century, various explorers reached land at various points and the true nature of Antarctica gradually became known. The world map was finally complete on the basis of exploration, not just on theoretical ideas.

Hippocrates and his followers explained health and disease by the balance of "humors," a theory that remained unchallenged for many centuries and eventually hampered the development of medicine. Yet Hippocrates freed medicine from religion and superstition and put it on a more scientific footing. Accurate observation of the course of an illness became important, as well as the healing power of nature. Herbs, massages, diets, and baths were prescribed for the treatment of disease, but psychosomatic treatments also had their place.

When Alexandria became the center of scientific activity, a number of scholars there made important discoveries. Herophilus of Chalcedon studied the functions of the brain and the nerves, and was the first to distinguish between arteries and veins. Greek medical teaching spread in Rome. Among the practitioners of medicine there, Galen became the best known. He experimented with animals and dissected them, formulating theories that were treated as dogma in medicine for the next 1500 years.

Mathematics. Mathematics occupied an important place in Greek science and was further developed than any of the other sciences. Mathematics is based entirely on reasoning—the scientific activity Greeks preferred most—and does not require observation or experimentation as physics does.

The Egyptians were concerned mainly with applied mathematics: sets of rules that can be used to solve specific problems. Thales, who according to tradition was familiar with Egyptian mathematics, was the first to formulate general mathematical laws for measuring and to prove theorems. He is considered to be the founder of geometry.

Pythagoras, in the fifth century BC, founded a school stressing high moral standards and the pursuit of science.

He ranked mathematics as the most important science. Pythagoras was convinced that the "natural order" could be expressed in numbers (*see* "Mathematics and Mysticism," p 36).

Mathematics also occupied an important position in the school of Plato. Plato himself, although not a mathematician, viewed geometry as the basis for the study of any science. Theaetetus and Eudoxus, who belonged to the school of Plato, developed the theory of incommensurable magnitudes and the theory of proportions, respectively. Menaechmus made the first study of conic sections—ellipses, parabolas, and hyperbolas—a class of curves that later proved to be of extreme importance to astronomers and physicists.

Geometry culminated with the Alexandrian mathematician Euclid. He was the author of the *Elements*, comprising 13 books that summarize and organize the geometric thought of the Greeks. The *Elements* is a coherent mathematical construction based on a small number of axioms from which are derived a large number of propositions by applying strictly logical rules. The *Elements* formed the basis for teaching geometry in schools well into the twentieth century.

Archimedes is often classed among the first-rank mathematicians in history. Although he is popularly known for his work in physical science (see below), he worked largely in the context of mathematics. Among his accomplishments are the demonstration that numbers as large as one likes can be written (which he showed by writing a numeral for the number of grains of sand it would take to fill the universe); finding the properties of spirals; the expert use of Eudoxus's method of exhaustion (mathematically the same as the integral calculus, although formally quite different); and finding the ratios of the volumes of various figures to one another, such as showing that the volume of a sphere is two-thirds that of a cylinder whose height is the diameter of the sphere and whose radius is the same as that of the sphere.

Like Euclid and Archimedes, Apollonius of Perga was Hellenistic rather than Greek. Many Hellenistic works have been lost, including works by Euclid and Archimedes, but Apollonius' works suffered more than most. His work on the conics—the circle, ellipse, parabola, and hyperbola—along with a treatise called *Cutting-off of a ratio* are the only survivors. Nevertheless, many of his works have been restored on the basis of comments written about them. Apollonius was the last great synthetic geometer until the end of the eighteenth century.

Diophantus, the "father of algebra," worked with mathematical ideas that are equivalent to solving equations in several variables for integral solutions. Such equations are still called diophantine today.

Physical Science. The fundamental nature of matter was one of the first problems of the early Greek natural philosophers. Thales believed that water is the basic constituent of all matter, while others believed it to be fire or air (*see* "The first scientists," p 21). From Democritus we have the idea that matter is built up of atoms (*see* "Early atomists," p 32), an idea that appears more promising in retrospect than it did at the time. Empedocles introduced the idea of elements (*see* "The elements," p 31). Although the Greek ideas on matter were based on philosophical speculation rather than observation and experiment, developments in physics and chemistry during the nineteenth and early twentieth centuries proved them to be close to the mark. Unfortunately, their ideas about motion were erroneous. Aristotle believed motion to be induced by the striving of each object to reach its natural place (*see* "Replacing Aristotle's physics," p 118).

Archimedes made a number of advances in physical science, starting the tradition of what is called mathematical physics today. Although levers and other simple machines were undoubtedly known earlier, Archimedes was the first to work out the mathematical law of the lever. Similarly, he developed the first applications of hydrostatics when he showed that a body immersed in a fluid would displace its own mass. There are famous legends connected with each of these discoveries. According to one, Archimedes used a system of levers to pull a fully loaded ship onto shore to demonstrate the idea expressed by the statement attributed to him "give me a lever long enough and a place to stand and I can move the Earth." The other has Archimedes discovering the laws of hydrostatics in the bath and running naked through the streets of Syracuse shouting "*Eureka*" ("I have found it").

Technology. Because society in antiquity was based on slavery, little incentive existed to develop technologies that would ease labor. The Greeks mastered the smelting of iron, and because iron ores were abundant, iron weapons and tools became widespread. In Alexandria, largely because of Egyptian influence, there was more interest in technology. Many consider Ctesibius to be the founder of the Alexandrian school of engineering. His younger contemporary, Philon of Byzantium, reported some of his technical achievements; among them were a force pump, a water organ, and a mechanically driven water clock. Hero of Alexandria described a series of automata and experimented with model steam engines. Archimedes applied scientific principles to technology. His most famous invention is the Archimedian screw, a device for raising water in irrigation systems.

On the other hand, the presence of slaves did nothing to discourage building aqueducts, bridges, and roads. While the Romans became the master of these, the first water-carrying tunnel through a mountain was a Greek achievement, being the work of Epalinus of Megara in the sixth century BC. The Romans also developed concrete and used it in many of their constructions.

OVERVIEW Part 2

Science in many lands and medieval science

With the disappearance of the last great centers of learning from antiquity—the Academy and Lyceum in Athens were closed down by the Byzantine emperor Justinian in 529 and the Museum of Alexandria, only a shadow of its former self, was destroyed by the Arabs in 641—scientific activity almost ceased in Europe. Although there was a revival among church scholars in the twelfth century, this was snuffed out in the general disarray following the Black Death in the fourteenth century. A true revival of science can be dated from the middle of the fifteenth century, when the fall of Constantinople to the Turks resulted in scholars bringing many Greek manuscripts into Europe in 1453. Printing also began about this time, changing the way that scientific ideas could be communicated. Thus, we use 530 and 1452 as the boundary dates for this period.

The decline of science in Europe

Several reasons for the decline of science in Europe between 530 and 1000 have been put forward by historians. For one, European culture was still strongly influenced by the Romans, who were notoriously little interested in theoretical science. With the disintegration of the Roman empire, society underwent several important changes; for example, the large cities disappeared, roads and aqueducts disintegrated, and trade became more limited. The general infrastructure in which learning and science could develop had ceased to exist.

Medicine was an exception. To an extent, it survived the Dark Ages because the Christians felt it to be their duty to take care of the sick. During the sixth century, the works of Hippocrates and Galen were studied at monasteries. In addition, the high level of teaching of medicine at Salerno during the ninth century heralded the revival of science during the later Middle Ages.

Arab science

The Islamic culture, which flourished from about 700 to 1300, played a key role in bridging the gap between the Hellenistic period and the Renaissance. During that period, the Islamic empire became the most advanced civilization in the Western world. The role of Islamic culture in the development of science is demonstrated by the large number of scientific terms with Arabian origins, such as *azimuth* and *algebra.*

There are several factors that contributed to the flourishing of science in the Islamic civilization. Because of intense commercial activity, the Arabs came into contact with a large number of cultures, such as the Indian and Chinese cultures (*see* "Indian science," p. 65, and "Science in China" p. 59). Several different cultures became part of the Islamic world: the Iranian, Turkish, Jewish, Orthodox and Nestorian Christians, and Gnostic, known as Sabian or Mandaean. Each of these civilizations had new ideas to contribute to Arab thinking.

A strong unifying factor in the Islamic empire, besides the Islamic religion, was the Arabic language, although various parts of the empire also used Persian, Syriac, and other languages. Many of the works of the ancients have been preserved because they were translated into Arabic. During the sixth century, many of the important Greek works were also translated into Syriac; when the Arabs conquered Syria, these works were translated into Arabic. Several Hindu works were also translated into Arabic.

A number of centers of learning appeared throughout the Islamic empire. Baghdad developed during the eighth century into one of the most important ones: Al-Ma'mun (786-833) founded a "House of Wisdom" there that contained an astronomical observatory. Many of the important Greek treatises, such as Galen's medical writings and Ptolemy's astronomy, were translated at the House of Wisdom. During the tenth century, Islamic Cordoba, in Spain, which became the richest and largest city in Europe, contained a library of 400,000 volumes.

The Arabs not only translated and preserved the scientific works of the ancients and Indians, they also contributed themselves to several scientific fields. In astronomy, they made a large number of accurate observations with instruments superior to those of the Greeks. In addition, they compiled astronomical tables that remained in use until the Renaissance. The Arabs revived astronomy by studying the ancients and repeating their observations. The Toledan tables, compiled by al-Zarkali (also known as Arzachel) about 1029-1087, became the basis of the Alfonsine tables that were published in Spain by order of Alfonso el Sabio (Alfonso X of Castile-León, 1252-1284). This compilation of planetary and stellar positions remained in use for the next three centuries.

Arabian mathematics blossomed in part because it combined the mathematical knowledge of the Greeks with that of the Indians. The introduction of Indian numerals, often called Arabic numerals, with their decimal place-value system, simplified calculations. However, Arab mathematicians were not content merely to preserve the Greek and Indian traditions; they added new ideas of their own, especially in solving equations, trigonometry, and numerical calculation. The term *algebra* is based on Muhammad ibn Musa Al-Khowarizmi's book *Al jabr w'al muqābalah* (Restoring and balancing, or possibly Equations and reduction). Also, the modern term *algorithm* comes from the first sentence of the Latin translation from that book: "*Algorismi dicit* . . ." (Al-Khowarizmi says . . .).

Chemistry developed into an experimental science among the Arabs; substances unknown to the Greeks, such as borax and sal-ammoniac, were prepared by Arab chemists.

In physics, as in astronomy, Arab scholars excelled in the craft of instrument making. Alhazen's *Treasury of optics* remained influential until the sixteenth century.

Medicine was highly developed, and a complete infrastructure for health care existed. For example, in Baghdad, 1000 government-licensed physicians practiced medicine. There were numerous hospitals and even mental institutions where humane treatment of patients was

Science in China

Chinese society has been known throughout history for the stability of its traditions and its bureaucracy. Yet, until about the fifteenth century, China was more successful than western Europe in applying scientific knowledge.

The Chinese discovered paper as early as 105 AD. The first printed text (in block printing) appeared in 868 AD. Around 100 BC the Chinese discovered that a magnet orients itself towards the North Pole, but they did not use magnets for navigation at sea until the tenth century. In 969 AD rockets were used in warfare. The Venetian traveler Marco Polo reported that the Chinese used firearms in 1237.

The escapement, the most important part of the mechanical clock, was invented in 725 AD. The Chinese were familiar with many other mechanical devices, such as the eccentric and the connecting rod, as well as the piston rod, long before they became known in Europe. Furnace bellows driven by waterwheels contributed to the astonishing developments in iron and steel production during the Sung period (960-1279 AD).

Besides their technological progress, Chinese civilization had gone far in developing theories on matter and living beings. The Chinese seem to have always believed that the blood circulated, for example. Isaac Newton's first law of motion, that a body will not stop moving unless stopped by an opposing force, was stated by Chinese philosophers almost 2000 years before Newton.

Large amounts of empirical data on a number of subjects were accumulated. Most notably, Chinese astronomy reached a high level during the eighth century BC; it was outstanding for the quality and quantity of observations. For example, the precise Chinese records of the supernova that was visible in 1054 AD allowed present-day astronomers to establish that the supernova was the origin of the Crab nebula.

The attitude of Chinese society toward nature was quite different from the attitude that developed in Europe during the Renaissance. The Chinese never separated the material from the sacred world, and did not have the conviction that people can dominate nature. They were not interested in developing a scientific method; thus their theories often remained divorced from observation and experimentation.

offered. However, the science of anatomy did not progress because dissection of corpses was not allowed by Islamic law.

The knowledge gathered by the Arabs found its way to Christian Europe through translations made in the twelfth century from Arabic into Latin.

The revival of science in Europe

Science returned to western Europe to some degree during the twelfth century. Although the Christian church had played an inhibiting role in the development of science in earlier centuries, it was the church that caused much of ancient learning to be preserved. The members of the clergy and of monastic orders were practically the only people who were literate. The emperor Charlemagne, who learned as an adult to read and tried unsuccessfully to learn to write, decreed in 787 that every monastery must establish a school. These cathedral schools became the forerunners of the first universities. Technology, especially crafts and farming, was actively pursued at monasteries. However, the strongest factor in the revival of science during that time in Europe was the establishment of contact with the Islamic culture.

Islamic civilization was at its height during the cultural low point in western Europe that followed Charlemagne. As cities with a more educated population began to develop in Europe, Christian scholars were eager to absorb the knowledge amassed by the Muslims. Toledo (Spain), which had remained a Christian bishopric throughout the Muslim occupation, was one of the important centers of Islamic learning. The city was conquered by Alfonso VI of Castile in 1085, and many scholars went there to study with the Arabs. The Christians mostly learned about the Islamic culture, however, through the Crusades.

A large number of Greek works became available to European scholars from 1150 to 1270. Some scholars, such as Adelard of Bath and Gerard of Cremona, learned Arabic. Gerard of Cremona translated Ptolemy's *Almagest* from Arabic into Latin as well as some of Aristotle's works that had been translated into Arabic, Euclid's *Elements*, and the works of Galen and Hippocrates. Adelard of Bath translated Al-Khowarizmi's astronomical tables. Robert of Chester translated Al-Khowarizmi's *Algebra*. By 1270 the whole corpus of Aristotle's work, a large part of it translated from the original Greek by William of Moerbeke, became known to medieval scholars.

The Scholastics were Christian philosophers of the thirteenth century. They set out to absorb the newly gained knowledge of the ancients and to reconcile it with the teachings of the church. St. Thomas Aquinas, one of the founders of the Scholastic school, argued that knowledge can be obtained through both religious faith and natural reason. He believed that Plato and Aristotle, especially Aristotle, were compatible with Christian religion. Some other Scholastics, such as Siger of Brabant and Boethius of Dacia (not the well-known Boethius), disagreed. Throughout the early thirteenth century, it became more and more apparent that Aristotle and the church were on a collision course. As early as 1210, the local synod decreed that certain of Aristotle's works could not be taught at the University of Paris. After all, they said, Aristotle's works imply that God did not create the world, that there can be no transubstantiation of the host and wine during communion, that miracles cannot occur, and that the soul does not survive the body. In 1277 the pope issued a condemnation of 219 propositions, including many from Thomas Aquinas, that were tainted with Aristotle's views.

During the fourteenth century, a number of scholars developed a new style of philosophy that was less tainted by Aristotelianism and therefore not banned under the condemnation of 1277. Roger Bacon wrote in his *Opus maius* that it is wrong to rely only on the authority of past scholars and that experiment is an important means of gaining knowledge. William of Ockham and Jean Buridan criticized Aristotle's theory of motion. Nicholas of Cusa (a cardinal in the church) challenged Aristotle's concept of the fixity of the Earth.

Major advances

Astronomy. Ptolemy's *Almagest* became the standard text for astronomy throughout the later Middle Ages. Astronomy was still based on Plato's principle that all observed motions of heavenly bodies had to be explained in terms of uniform circular motions. Ptolemy's and Aristotle's views became incorporated into church dogma, mainly through the efforts of St. Thomas Aquinas. Aristotle's cosmology required a "prime mover" that keeps the planets and stars moving. The existence of a prime mover became for St. Thomas his "first proof" of the existence of God.

Although the Arabs accepted Ptolemy's system of cycles and epicycles, they greatly improved observational techniques and developed trigonometry as a part of their astronomical work.

Life science. Later medieval biology was strongly influenced by Aristotle's method of investigation: try to find the function and purpose of organic structures. Botany and zoology became separate disciplines. The main interest in botany was medical, while zoology often played a moral and didactic role, emphasizing fables more than facts. Both sciences incorporated tales and fables of all kinds; famous were the so-called bestiaries, stories describing incredible animals and monsters, usually believed literally by the population. The most accomplished biologist was Albertus Magnus, who studied plants all over Germany not just for medical or agricultural reasons, but also for scientific purposes as well. He also studied a large number of animals, birds, and insects, and ridiculed the fantastic stories from the bestiaries.

The monasteries generally preserved the medical heritage of Greece and Rome, and medicine became the most successful practical art in the Middle Ages. During the eleventh century, medicine underwent a revival at Salerno (Italy), where it reached a high level because of contact with the Arabs in nearby Sicily. During the twelfth century, Montpellier (France) became a medical center, and during the thirteenth century, medical schools appeared in Bologna, Padua, and Paris.

Medical practice relied on the Hippocratic method combined with the use of herbs and drugs, although astrological influences also were believed to play a role in the course of an illness. Drugs based on arsenic, sulfur, and mercury were used, especially mercury ointments for the treatment of skin disease. Opium was used as an anesthetic during surgery. The art of ophthalmology, acquired from Arab physicians, reached a high level and operations removing cataracts were performed successfully.

Mathematics. Mathematics was at a very low level during the early Middle Ages. Most calculations were done on the abacus because, before the advent of Hindu-Arabic numerals, mathematical operations were difficult to perform. Leonardo of Pisa, also known as Leonardo Fibonacci, introduced Hindu-Arabic numerals in Europe, although they were known previously to some mathematicians. He also is known for the Fibonacci series, a mathematical series in which each term is the sum of the two preceding terms (1, 1, 2, 3, 5, 8, ...).

Nicolas Oresme introduced notions that correspond to the idea of rational (fractional) exponents as well as a concept similar to that of a function. He also introduced a graphical system for studying mathematical curves. While his graphs for uniform motion were not based on a coordinate system in the Cartesian sense, they implied (for the specific examples used) the fundamental law of the calculus: the way a function changes determines the area under a curve describing the function; however, such an interpretation is possible only if one already knows calculus.

Physical sciences. The physical sciences were dominated by the views of the ancients, especially by Aristotle's ideas on motion. It was believed that motion is possible only if something continuously pushes the object being moved. William of Ockham was one of the first to introduce the concept of *impetus* and to reject the idea of a prime mover and thus the validity of St. Thomas's first proof of the existence of God. He argued that God put the celestial bodies in motion during the Creation, and that they keep moving because they retain the impetus conferred upon them. Jean Buridan perfected Ockham's theory and Albert of Saxony distinguished between uniform and irregular motion.

Although magnetism was known in antiquity, one of the earliest descriptions of the behavior of magnets is from Petrus Peregrinus. In his *Epistola de magnete* he describes an experimental method of studying magnetism; for this, he is viewed by many as the first experimental physicist. Robert Grosseteste and Roger Bacon performed optical experiments; Bacon viewed experimentation as an important means of increasing knowledge.

Chemistry was dominated by alchemy, taken over from Arab sources. The alchemists searched for a method of making gold, and a large number of manuscripts appeared on that subject. The church vigorously opposed alchemy, but there were practitioners of alchemy within its ranks. Alchemy led to experimentation; several new chemicals, such as mineral acids, and some practical applications of alchemic techniques appeared. Several types of distillation methods were improved; for example, water cooling of the condensing tube was introduced. The distillation of alcohol appeared during the twelfth century, and *aqua vitae*, 96 percent alcohol or 192 proof, was obtained during the thirteenth century by redistillation. Toward the end of the thirteenth century, the first oil-based paints appeared.

Technology. Because society in the Middle Ages was not based on slavery, and because of the emergence of trade and artisans, technology made striking progress. Many of the devices used, such as waterwheels, geared wheels, and windmills, were known in antiquity—although windmills were first described about 600 AD—but it is only during the Middle Ages that these devices came into use on a large scale. In 1086 there were some 5000 water mills in England. Waterwheels were used to drive trip hammers for crushing bark or for tanning; later waterwheels drove forge hammers and bellows in forges. The size of furnaces to reduce iron ores increased, and several types of carbon steel and cast iron were produced, although the exact role of carbon content in iron was not understood.

Paper-making technology, introduced from China by the Arabs, reached Europe during the twelfth century, and paper mills were established in several cities. This paved the way for printing in Europe, which began at the very end of this period, around 1440. The spinning wheel also appeared around that time.

Agriculture was improved by the introduction of the iron plowshare, about 1000 AD, and the horse collar, in which the pull is placed on the shoulders of the horse instead of the windpipe. The more efficient agriculture and food production resulted in an increased wealth: cities blossomed and commerce became more intensive.

Virtually all of these technological advances were known earlier in China, but in most cases it is impossible to determine which inventions diffused from China.

The empirical technology of engineering and architecture underwent its greatest growth since the time of the Romans. Medieval cathedrals developed over the centuries as builders found new ways to solve the problems of building very large structures from stone. Similar technology could be applied to other large structures, such as town halls or bridges.

OVERVIEW Part 3

The Renaissance and the Scientific Revolution

One way to date the beginning of the Renaissance is from May 29, 1453, the day the Turks captured the city of Constantinople and many Greek-speaking scholars escaped to the West. The scholars brought with them classical manuscripts in Greek along with the ability to translate the ancient writings into Latin, the common language of the ancient writings into Latin, the common language of learning in Europe at the time. However, the roots of the Renaissance go back further. After the depletion of the population of Europe in the fourteenth century from the Black Death, cities and towns rebounded with vigor. A population that is suddenly much smaller must find new ways to function. Mechanical devices and more trade make up to some extent for missing people.

There was much change going on around 1453 for other reasons as well. Movable type was reinvented in Europe around 1440 and the Gutenberg 42-line Bible was printed just a year after the fall of Constantinople. The Moors were driven from Spain the year that Columbus reached America, 1492. In 1498 Vasco da Gama reached India by sailing around the Cape of Good Hope. And Luther nailed his 95 Theses to the church door in Wittenberg in 1517, starting the Protestant Reformation.

But if it barely possible to date the beginning of the Renaissance, it is almost impossible to say when the Renaissance ended. This is especially true for science. Gradually, scientists of the Renaissance began to perform experiments more frequently. The era of the Scientific Revolution that starts in the later Renaissance also has no specific ending. We conclude this chapter just before the founding of England's Royal Society, which inaugurates a new and better organized era in science dominated by Newton and Leibniz, an era in which the Scientific Revolution is completed.

The early Renaissance

The fifteenth century was primarily a time of the absorption of classical learning and the adoption of Arabic mathematics. It was much more a period of change in arts and letters than in science. When one thinks of the Renaissance, one thinks of Leonardo da Vinci and Michelangelo, not Regiomontanus, Paracelsus, and Tartaglia. Alchemy and astrology were more important than chemistry and astronomy during this time (*see* "The last alchemists," p 88). Physics had to absorb Aristotle's work before it could develop the modern approach to physical motion (*see* "Replacing Aristotle's physics," p 118).

Another major influence that had to be absorbed is often overlooked. The explorers of both the New World and the East discovered a wealth of previously unknown plants and animals. Although the short-term effect was a sudden change in the diets of the peoples of Europe and Asia, the long-term importance was that these discoveries led to the classification schemes of John Ray and Carolus Linnaeus.

In the continuation of a trend that predates the Renaissance, artists, especially painters, made significant contributions to science. The development of perspective drawing and the dissection of human bodies were valuable to both art and science. The artist Albrecht Dürer, for example, wrote papers on both geometry and anatomy. The most notable example of the artist-scientist during this period was Leonardo da Vinci, a remarkable inventor and engineer as well as an artist skilled in human anatomy. Even Michelangelo functioned as an engineer in his designs for the dome of St. Peter's and other buildings, as well as being in charge for a time of the fortification of Florence (Italy). From these people and others like them the term *Renaissance man* came to mean one skilled in many fields.

The later Renaissance

The Renaissance, which began in Italy, reached northern Europe in the sixteenth century. There it joined with the new values of the Reformation. With the Renaissance came economic transformation: markets were opened on a world scale and trade boomed in the cities. By 1603 the English philosopher and scientist Francis Bacon had characterized the new century as an age distinguished by "the opening of the world by navigation and commerce and the further discovery of knowledge." Bacon was

1453-1659

among the first to view science as a powerful tool to conquer nature. In his fable *New Atlantis* he wrote that science's aim is "the enlarging of the bounds of human empire; to the effecting of all things possible."

The Scientific Revolution

Publication of Copernicus's heliocentric theory and Vesalius's anatomy in 1543 is a good beginning point for the Scientific Revolution (*see,* "1543: A remarkable year in publishing," p 108). Throughout the West, modern science began to take shape in many ways. The first scientific societies, such as the *Academia Secretorum Naturae* (Academy of the Secrets of Nature) and the *Accademia dei Lincei*, were formed in Italy during this period. The former society was founded in 1560 but was soon suppressed by the Inquisition. The *Accademia dei Lincei* (the exact meaning of *Lincei* is not known; the academy's symbol is a lynx), founded in 1603, is the oldest existing scientific society.

Both the Catholic church and the Protestant church of Martin Luther opposed the views of Copernicus, but the Catholic church persisted in its opposition and reaped most of the blame for unscientific attitudes. When the Inquisition burned Giordano Bruno in 1600 for his mystical heresies, it also appeared to condemn his Copernican views. By 1616, Copernicus's *De revolutionibus* was on the Catholic church's Index of prohibited books, and Galileo was warned not to promote Copernican ideas. Galileo's *Dialogues on two chief world systems* was viewed as possibly concealing some of Bruno's heresies and as breaking the ban on promoting Copernican views. The Catholic church succeeded in forcing Galileo to abjure his Copernican beliefs in 1633. More than 100 years passed before the church allowed the construction of a mausoleum for Galileo in 1734. Much later the church lifted its ban on the publication of works that defended the Copernican system. Several decrees to that effect were issued from 1757 to 1822.

Throughout the period, mathematicians introduced various symbols and conventions, including the cross as a multiplication sign, letters for constants and variables, and exponents. These greatly simplified the communication of mathematical ideas; as they gained acceptance, they made mathematics an almost universal language.

Not only were mathematical symbols beginning to make a difference, but the tools of mathematics expanded rapidly during the period. The new branches of the subject were symbolic algebra, analytic geometry, probability, and logarithms.

Mathematics is an intellectual tool of science, but the hardware of science also began to assume modern form during the period. The development of spectacles toward the end of the Middle Ages offered opportunities to experiment with lenses. In turn, this led to the invention of the telescope and the simple microscope around the beginning of the seventeenth century. Galileo's observations of the stability of the beat of a pendulum led to Huygens's invention of the pendulum clock (*see* "The rise of time," p 164). Galileo himself made one of the first thermometers (*see* "Galileo and measurement," p 137).

Galileo also introduced experimentation into science, thus laying the foundation of science as we know it today. His detailed study of motion and his method of expressing natural events mathematically opened the way to Newton's discovery of universal gravitation.

Major advances

Astronomy. With the translation of Ptolemy into Latin for the first time, astronomy became a science again in the West, but one founded on incorrect premises. Few Renaissance scholars questioned Ptolemy's scheme, although Nicholas of Cusa, whose thinking in general was far in advance of his time, presaged Copernicus in 1440 by claiming that Earth revolves about the sun. Georg von Peurbach, although he had met Nicholas of Cusa, accepted Ptolemy's scheme and revised it by correcting errors that had creeped in over the years.

Galileo's introduction of the astronomical telescope in 1609 changed astronomy forever (*see* "Galileo and his telescope," p 126). Kepler went beyond Copernicus to work out the detailed movements of the planets; he found empirical laws that governed these movements.

Life science. Most of the progress in life science during this period was in medicine, especially anatomy. The invention of printing led to books on surgery and medicine. Although these books often contained many errors, knowledge of these subjects was much more widely available. Anatomy was based primarily on the works of Galen, especially at the beginning of the period, but the practice of dissecting corpses in front of medical students in Italy led careful observers to disagree with Galen by the end of the period (*see* "1543: A great year in publishing, p 108).

Another factor in gaining a better understanding of anatomy was the study of musculature by painters and sculptors, most notably Leonardo da Vinci. With the discovery of the circulation of the blood by Harvey, a general picture of the body as a system of tubes, ducts, and valves grew during the course of the period. The mechanical view of the body became so prevalent that it acquired a name—iatromathematics, called iatrophysics today (*iatro-* means pertaining to medicine or healing). Also in the field of medicine, Paracelsus, heavily influenced by alchemy, became a strong advocate of the use of chemical medicines.

There were also notable gains in botany. Scientists such as Otto Brunfels and Leonhard Fuchs published works, influenced by Latin translations of Aristotle and Theophrastus, in which various plants were described or pictured (*see* "Peppers and a whole lot more," p 93). In the compendiums of Konrad Gesner, all known (and a few never to be known: Gesner still believed in mythical creatures) animals and plants were described. By the end of the sixteenth century, Gerard's *Herbal* stuck to real plants, but often ascribed almost magical properties to them.

Mathematics. As Hindu-Arabic numerals continued to replace the clumsy Roman system, various textbooks appeared that taught how to apply the new symbols. Standard algorithms and bookkeeping methods were introduced. Tables of trigonometric functions were printed and applied to new surveying techniques. Military uses of mathematics included ballistics and the improvement of fortifications. There was also gradual development of the symbolism of mathematics (*see* "Inventing signs," p 94). Calculation also advanced in other ways. Pascal invented an adding machine, and Napier discovered logarithms. All of these developments made mathematics easier and more a part of daily life.

On a more theoretical level, mathematicians were beginning to expand their understanding of what constitutes a number. Irrational numbers gained steady, if slow, acceptance as numbers, not merely magnitudes. Following the irrationals were the negatives. Even writers who refused to accept negative solutions to equations discovered that algebra could be greatly simplified by accepting negative coefficients. Soon the best mathematicians were using negative numbers regularly, but still expressing skepticism about them. Imaginary numbers began to have some currency later in the period.

A major achievement of mathematics during this period was the algebraic solution of the general cubic and quartic equations—that is, polynomial equations whose highest power of the unknown variable is three or four (*see* "A great scoundrel," p 107).

The publication of a new edition of the works of Diophantus led Fermat and his circle to advance pure number theory. Much of their work was not published at the time. Similarly, probability theory was invented in an exchange of letters between Fermat and Pascal. Analytic geometry was developed by Fermat, who did not publish his discovery, and by Descartes, who published his finding in an appendix to a work of philosophy, the *Discourse on method.*

Physical science. As with mathematics, much of the development of physical science during the Renaissance had a strongly practical side to it. Thus, we find advances and summaries of knowledge in such fields as mining, assaying, distillation, and ballistics. In the early part of the period, discoveries outside of practical fields were isolated instances. Alchemists were probably making some progress in chemistry, but their interpretations of what they were doing and their tendency to keep results secret offered little to science.

A notable development took place when Galileo performed a series of experiments with moving bodies, making physics into an experimental science and founding the field of dynamics.

Technology. The greatest technological innovation of the period was printing from movable type; however, this may be characterized as a reinvention. Movable type had been invented in the eleventh century by the Chinese, who had earlier invented printing. Chinese movable type was not a major influence, however, because ideographic writing is not as conducive to movable type as is the Roman alphabet. Gutenberg probably did not get his idea from Chinese sources, even secondhand. His invention stems from about 1440, although the date is not certain. There is some evidence that movable type also was invented in Holland around the same time, which would suggest that the idea was generally known.

Printing and paper, however, almost assuredly did reach the West from China, although indirectly. Thus, Gutenberg's reinvention of movable type was built on a Chinese foundation.

Other technological innovations of the period furthered understanding of space and time. Maps, needed by sailors following the routes of the great explorers, were improved. Globes were introduced even before the Americas were known in Europe. Clocks based on suspended weights and toothed escapements had been introduced in Europe about a century before, primarily as tower clocks that rang the hours. During the Renaissance there was constant improvement of their mechanisms.

The most dramatic technological ideas of the early Renaissance come from Leonardo's notebooks. Written in mirror-writing and illustrated with numerous sketches and drawings, the notebooks provide an unparalleled record of the thoughts of a man far ahead of his time. Leonardo is given some credit for the invention of the helicopter, the parachute, and other devices. In many cases it is not clear whether Leonardo made working models of his devices. Remarkable as his technical ideas were, they were mostly secret and had little actual influence on the progress of science.

Advances in measuring devices and observational tools were another important technological feat of the period. Vacuum pumps, developed by Guericke and Boyle, also became tools of the new science (*see* "A lot out of nothing," p 142).

Commercial technology related to mining and smelting became important. This led to some of the early literature of technology, such as the works of Agricola and Biringuccio.

Peppers and a whole lot more

Columbus, from his first voyage onward, met Native Americans who were farmers. Columbus was looking for gold and spices; although he did not find much in the way of gold, he believed he had discovered spices, for he thought that a Caribbean shrub was cinnamon and that other plants were those reported from the East by Marco Polo. It is not clear whether he thought the *Capsicum* of the New World—the common green or red pepper—to be the same as black pepper, although he clearly refers to "very hot spices" that must have been *Capsicum*. By 1493, Matyr (Pietro Martire de Anghiera) was using the accounts of Columbus's first voyage to describe *Capsicum,* which he called peppers, although clearly differentiating the American peppers from black pepper.

Although archaeological remains in the Americas make it clear that *Capsicum* originated there, there are puzzling aspects to how it traveled from the Americas, which it did quite speedily. The padres that accompanied the Spanish explorers brought back seeds of many plants, including *Capsicum,* for their monastery gardens. After that, the pattern of distribution becomes unclear.

For example, most botanists before 1600 thought that the *Capsicum* had been imported from India, not the Americas. There was a reason for this belief. There is good evidence that *Capsicum* first reached Germany before 1542 from India, not from the Americas. Thus, in less than 50 years, *Capsicum* had circled three-quarters of the way around the globe, traveling in what would seem to be the wrong direction.

The conventional view is that Portuguese sailors took *Capsicum* to their colonies in India sometime between their first voyages in 1498 and 1513. There, peppers could have been introduced to the Indians, as well as to the Ottoman Turks, who besieged the Portuguese colonies in 1513 and 1538. Then the Turks carried peppers with them to the Balkan peninsula, which they occupied. Botanists in Europe got them from the Turks, who said the peppers were Indian. The tale becomes somewhat complicated because early writers attributed the origin of the name *Capsicum* to a thirteenth-century botanist, who, of course, wrote before Columbus's voyage.

The Indian connection remains somewhat of a mystery, especially because *Capsicum* is so much a part of Indian food. It should be noted, also, that traditional cooking from some regions of China is heavily dependent on *Capsicum*.

A further mystery is that *Capsicum* was being cultivated in Melanesia when the first Europeans arrived. Theories that explain this involve native traders bringing the plants by stages from India.

Of course, *Capsicum* quickly settled into Europe, becoming an essential part of the cuisine of Italy, for example, and Hungary (in the form of paprika). Other American food plants also quickly became naturalized, including the tomato, the potato, and the American bean. It is difficult to imagine any European cuisine before 1500 as a result.

The Americas also obtained European food plants from the early colonists. At the same time they acquired a multitude of weeds. Many of the common roadside weeds across the United States, such as Queen Anne's Lace (the wild carrot), are imports.

It is not surprising that the flora of the Old and New Worlds should be different after millions of years of separation, especially with regard to domesticated plants. The only domesticated plant found in both places before Columbus's voyages is cotton. How cotton was spread is an even greater mystery than how the *Capsicum* got to India.

The great plant interchange had great significance for science. About the same time as the new plants began to reach Europe, so did a rediscovery of the works of the first great botanist, Theophrastus, whose work had been stimulated in part by the Greek discovery of Indian flora in the conquests of Alexander. This rediscovery, along with the arrival of thousands of plants from the New World, contributed to the development of botany in the works of Leonard Fuchs, Konrad von Gesner, Charles Lécluse (Clusius), Caspar Bauhin, John Ray, and, ultimately, Linnaeus. The New World flora continued to have an impact well into the nineteenth century, forming one of the main influences on the ideas of Charles Darwin and those of Alfred Wallace, who had traveled to the Amazon basin and written about it before his sojourn in the East Indies.

OVERVIEW

Part 4

The Newtonian epoch

Science developed fully during the years of the Scientific Revolution, but in the period from 1660 to 1734 science found the forms of organization it had lacked before. A convenient way to date the period of developing organization is from the founding of the Royal Society. This period was dominated largely by the ideas of Isaac Newton and, to a lesser degree, Gottfried Wilhelm Leibniz. In this book, we start the following period, known as the Enlightenment, in 1735 with the publication of the Linnaean scheme for classifying organisms.

Scientific societies, such as the Royal Society in England and the *Académie des Sciences* in France, not only stimulated scientific inquiry, but also made meetings between scientists possible and increased scientific communication. The creation of scientific institutions, such as the Greenwich Observatory or the *Accademia del Cimento*, made scientific research a more organized undertaking. Learned journals, such as the *Philosophical Transactions* and the *Journal des Savants*, provided a means of circulating ideas superior to the traditional means of correspondence between scholars. Mathematicians did not have their scientific institutions yet and still relied on correspondence for communicating their ideas, a situation which often led to disputes of priority.

The scientific method

The most important scientific work of the second half of the seventeenth century was Newton's *Principia*. Not only did it become the foundation of physics for the next 200 years, it formed the basis of the scientific method that slowly made its entry into the study of natural phenomena. Unlike Descartes, who advocated the deduction of scientific laws from metaphysical principles, Newton based his theories on the careful examination of natural phenomena. Newton called his method the "method of analysis and

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Scientific societies

One of the reasons for the stagnation of science during the Middle Ages was that very few could learn of new discoveries. The printing press did not exist, and there were no organizations that collected, registered, and disseminated scientific information.

The first scientific societies made their appearance during the seventeenth century. Patterned after existing literary societies, the *Accademia dei Lincei* (the Academy of the Lynxes) was founded early in the century in Rome and counted Galileo among its members. The society was short-lived, however, (although later revived and still in existence today) and was followed in 1630 by the *Accademia del Cimento* (Academy of Experiment) in Florence. In France the *Académie des Sciences*, founded in 1666, served to bring together eminent scientists from outside as well as from France. Christiaan Huygens from Holland, Ole Römer from Denmark, and Giovanni Domenico Cassini from Italy joined the *Académie*.

In England the Royal Society was the outgrowth of a tradition that became established at Gresham College in London. Gresham College was founded with an endowment by Sir Thomas Gresham, who was the financial adviser to Elizabeth I. Gresham College housed seven professorships: divinity, astronomy, music, geometry, law, physics, and rhetoric; the professorships of astronomy and geometry were the first in those disciplines in England.

A group of scholars started meeting informally in 1645 at the lodgings of Samuel Foster who was the Gresham professor of Astronomy. Foster, who died in 1652, was succeeded by Lawrence Rooke, who continued the tradition of weekly meetings. In 1657 Rooke started teaching geometry and Christopher Wren became Gresham professor of astronomy at the age of 25. The group, which began meeting twice a week, following the lectures of Wren and of Rooke, included William Brouncker, John Wilkins, and Robert Boyle. On November 28, 1660, the group decided to organize itself as a scientific society. John Wilkins became chairman and a few days later Charles II approved the society.

The Royal Society is today the oldest scientific society in existence continuously since its founding: its journal, *Philosophical Transactions*, founded in 1664, is the oldest existing scientific journal.

1660-1734

synthesis," a procedure that included both an inductive and a deductive stage. Theories are formulated from observations; these theories are then used to predict other phenomena. However, in practice, science does not operate strictly according to scientific method. Newton's most important discoveries were probably the product of intuition, which he later backed up with experiment, reasoning, and mathematics.

Every natural phenomenon, according to Newton, could ultimately be explained by mathematical law, an approach to science not necessarily antagonistic to religion. In fact, Newton and Leibniz were both deeply religious. For example, Leibniz interpreted physical laws as nature's way of achieving a maximum or minimum of certain physical quantities. The presence of a direction in nature's laws implied for him the presence of a "Perfect Being" that created the universe.

It was during this time, however, that the separation of physics and metaphysics (or philosophy) took place. For example, Newton accepted the mathematical description of gravity, knowing full well that his laws of gravitation said nothing about the nature or cause of gravitation. Newton refused to frame hypotheses that were not verifiable, unlike René Descartes, who hypothesized the existence of vortices to explain gravitation.

Observation and experimentation became the pillars of scientific activity. The idea that real knowledge and wisdom could be found only in the writings of the ancients lost ground gradually. Scientists ceased to rely on the old masters, such as Aristotle, and started to study the results of their own observations and experiments when formulating theories. They began recording phenomena in terms of values such as weight, volume, or temperature. Scientific instruments became widely available in every major town. The development of a pendulum that kept perfect time by Christiaan Huygens and the invention of the balance spring by Robert Hooke made the clock a precision instrument.

Scientists, lacking the present-day concept of energy, tried to grasp such qualities as heat, electricity, magnetism, and chemical energy by describing them in terms of material, weightless fluids capable of flowing through solids. The wide experimentation of this period resulted in many observed phenomena that were not understood. Nevertheless, these experiments formed the basis for the theoretical advances in physics and chemistry at the end of the eighteenth and beginning of the nineteenth centuries.

Unity of the sciences

Newton's discovery that a single law gave an accurate description of phenomena on Earth as well as in celestial space broke down the long held belief that the heavenly bodies were of special and divine nature. Astronomy became an extension of Newton's mechanics and the return of the great comet of 1682 in 1758—at the time predicted by Edmund Halley—was viewed as the ultimate confirmation of the validity of Newton's theory of gravitation.

Science, still called "natural philosophy," was not yet divided into the disciplines we know today. Natural philosophy encompassed all phenomena of nature, including astronomy, optics, statics, hydraulics, and mathematics. Chemistry was considered to be closely allied to medicine.

Major advances

Astronomy. Newton's theory of gravitation provided a theoretical basis for the Copernican system and Kepler's laws. Newton's work was also the starting point of a new field, celestial mechanics, that was to dominate astronomy for the next 200 years (*see* "Newton's *Principia*," p 148).

Telescopes were greatly improved as both the reflecting telescope and the achromatic lens were introduced. They pushed further the limits of observational space. The idea that the sun is but one of myriads of stars led to the view that human beings are not the center of the world, as exemplified in Bernard Fontenelle's book, *De la pluralité des mondes*. The introduction of micrometers also improved the ability of astronomers to map stars.

Edmund Halley and Giovanni Domenico Cassini were

Newton's Principia

The greatest breakthroughs in physics occur when someone understands that apparently different phenomena have the same underlying cause. One of the great unifiers was Isaac Newton. Newton was the first to demonstrate that the falling of objects towards Earth's surface, the motion of the moon around Earth, the motion of planets around the sun, and the odd trajectories of the comets are all governed by one law: the law of universal gravitation.

However, the idea of universal gravitation only became clearly formed in Newton's mind in the 1680s, when he was preparing the manuscript for his *Principia*. He had had a first inkling of this idea some 20 years earlier. At the end of his life, Newton related that he started wondering whether one could consider the moon as falling toward Earth when he observed an apple falling from a tree.

In 1666 Newton studied circular motion. He found that the force acting on a circling body is inversely proportional to the square of the distance of the body from the point around which it rotates. This result was also found by Christiaan Huygens, who published it in his *Horologium oscillatorium* in 1673.

Newton tried to apply this concept to the Earth-moon system and to the planets. He realized that the motion of the moon could be viewed as having two components. One of these components is the moon's fall toward Earth; the other is its motion in a straight line. Both motions occur at once, resulting in the nearly circular path of the moon. In the absence of Earth, the moon would move on a straight line. Its path is curved toward Earth because of Earth's gravitational attraction.

Newton first determined how much the moon's motion deviates from a straight line. He then compared the pull acting on the moon with the pull acting on a body on the surface of Earth. Newton determined that a body dropped at Earth's surface will fall 490 cm (16 ft) in the first second. He then found that the moon deviates from a straight path—and thus "falls" toward Earth—over 366 cm (12 ft) during one hour. If the moon were at the surface of Earth it would fall 490×3600 cm (16×3600 ft) in an hour. Now Newton compared this with the inverse square law that he had derived for rotating bodies on Earth. Since the moon is about 60 Earth radii from Earth, it would be accelerated toward Earth 60^2 (3600) times slower, which is approximately the case based on observation. (He actually found this factor to be 4000; the error was caused because Newton used the incorrect value for the size of Earth.)

Newton came to the conclusion that a force inversely proportional to the square of the distance from a body to its center of rotation keeps the moon and planets in their orbits. In 1645 the French astronomer Ismael Boulliau had also suggested, without giving proof, that a central force inversely proportional to the square of their distance from the sun might keep the planets in their orbits.

For a period after 1666, however, Newton turned his attention to optics and chemistry. In 1679 he again became interested in planetary orbits when Robert Hooke asked him to demonstrate that a planet would move in an elliptical orbit when subjected to a central force inversely proportional to the square of its distance from the sun. Newton found a mathematical proof, but never forwarded it to Hooke.

Christopher Wren and Edmund Halley were also investigating the problem, but neither could solve it. In 1684 Halley, who was the clerk of the Royal Society, visited Newton and asked him what he thought the orbit of a planet might be under an inverse-square law. Newton immediately replied, "An ellipse, for I have calculated it." Halley asked him to produce his paper with the calculations. Newton replied that he had mislaid this paper, but that he would start over with his calculations.

A few months later Halley received a paper from Newton called *De motum corporum in gyrum* (On the motion of revolving bodies), which Halley presented to the Royal Society. Halley's interest spurred Newton to develop his ideas further. Over the next two and a half years he wrote the *Principia*. Halley edited the sections of the manuscript Newton sent him and saw it through the press, at one time employing two printers to speed up the process. Because the Royal Society had no funds available at this time, Halley paid for the printing of the *Principia* from his own pocket.

At an early stage of the writing of the *Principia*, Hooke discovered that Newton did not mention him in connection with the inverse-square law, which he believed he had discovered prior to Newton. Hooke, who never had given a mathematical proof, attacked Newton, and the dispute over the priority of the discovery furthered the bitter feud that had long existed between the two scientists.

The *Principia* was published late in 1687. Unlike Galileo, who wrote his books in Italian, Newton wrote the *Principia* entirely in Latin. Although he had developed calculus during earlier years, he drafted the book using classical geometry—as was the custom at that time—to tackle physical problems.

Book I of the *Principia* contains Newton's three laws of motion and a discussion of orbital motion. Book II deals with the motion of fluids and attempts to prove that the vortex model proposed by Descartes cannot explain the motion of celestial bodies. Book III, *The System of the World,* contains the proposition that gravity is proportional to mass. In this book, Newton discusses applications of his theory to planetary orbits. He shows how his theory accounts for the irregularities of the motion of the moon, as well as the trajectories of comets.

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the leading astronomers of the day. Halley discovered periodicity of comets and proper motion of stars; he also started to map the sky as seen from the Southern Hemisphere. Cassini explored the solar system and discovered much about its planets and moons.

Biology. Better microscopes changed the view held by Descartes that living animals are relatively simple machines. His mechanistic interpretation of conception was displaced by the discovery of spermatozoa and by the discovery of the production of eggs in viviparous animals.

The transmission of characteristics proper to each species formed a fundamental problem. Jan Swammerdam formulated his "preexistence theory," which assumed that the seeds of all living creatures are formed during the creation of the world, and that each generation is contained in the one before.

Anton van Leeuwenhoek, who persisted in using powerful simple microscopes (with only one lens), became the first to realize that the world is filled with creatures too small to be seen with the naked eye. His investigations of protists and sperm as well as his observations of bacteria revealed a new world. Hooke also investigated the invisible world, being the first to notice and name cells.

John Ray and others worked at classifying plants and animals, being the precursors to Carolus Linnaeus. Physiology improved, as Marcello Malpighi studied the lungs, nervous system, and the physiology of invertebrates, and Regnier de Graaf investigated the reproductive system.

Chemistry. Until this period, the study of matter still relied almost completely on the traditional views of the alchemists, which incorporated a mixture of mystical and spiritualistic notions and empirical results. Jan Baptista van Helmont, and especially Robert Boyle, were instrumental in establishing chemistry as a rational and experimental science. Boyle introduced such concepts as elements, acids, and alkalis, developed Boyle's law of gases (although Edmé Mariotte independently discovered the same law), and discovered hydrogen and phosphorus (the latter independently discovered by Hennig Brand).

While little theoretical advance was made during the period in chemistry, a number of new substances were discovered. The major advances of the next period would not have been possible without the basic data that were developed during this one. One development, however, probably held chemistry back, the phlogiston theory (*see* "Phlogiston," p 182).

Mathematics. In mathematics, everything led toward the development near the end of the seventeenth century of the differential and integral calculus by both Newton and Leibniz; however, there were many strides forward in side branches. The role of mathematics in the natural sciences also changed drastically. Mathematics became fully the language of science. Leibniz promoted mathematics to the level of a "universal language," hoping it could be applied in domains other than scientific ones that require logical reasoning.

Statistics got started with the work of John Graunt, Jan de Witt, John Arbuthnot, and Abraham De Moivre (*see* "The first statistician", p 150). At the same time, the Bernoulli family continued to develop probability theory.

New tools were developed that are still useful today. Mathematical induction, known earlier but popularized by the posthumous publication of a book by Blaise Pascal, is a method for proving the truth of a statement about integers. The calculus of variations, developed initially by Jacques Bernoulli, is a method for finding the maximum or minimum of a function.

Medicine. Progress in biology, such as fundamental observations with microscopes, had an impact on medicine that would be felt when people started to apply their learning. Anatomists continued their description of the parts of the human body, such as the brain and the ear. Bernardino Rammazzini became the first doctor to note that certain kinds of cancer can be associated with environmental effects. The practice of inoculating children with smallpox spread from Turkey to England and its American colonies. Basic physiological measurements became easier with the availability of better thermometers and the first experiments in finding blood pressure.

Physics. The major development in physics was Newton's formulation of his laws of motion, foreshadowed by Galileo in the seventeenth century. Galileo's work had shown the need for a force to keep planets in their orbits. Newton's law of universal gravitation provided the theoretical foundation for Johann Kepler's laws and Galileo's observations. Descartes' theory of vortices remained the only one accepted in France for a while, but it was discarded when sufficient proof for the validity of Newton's theory became available (*see* "Verifying Newton's theory of gravitation," p 178).

There were also many advances in the theoretical understanding of light, ranging from the first mathematical treatment of refraction to the discovery of the speed of light (*see* "The nature of light," p 172, and "The velocity of light," p 160). Both the wave and particle theories of light were advanced during this time, ultimately to be superseded in the twentieth century by the quantum theory, which combines wave and particle aspects.

After Otto von Guericke discovered how to create large amounts of static electricity, the move to investigate electric phenomena gained momentum, although it was to reach greater heights later in the eighteenth and early nineteenth centuries (*see* "Electricity and magnetism," p 270).

Technology. The first steam engines, pumping water out of coal mines, appeared in England. More coal could be mined from deeper levels, clearing the way for Britain's Industrial Revolution. In addition, Abraham Darby discovered how to make iron with coal, making coal even more important to the new technology.

New inventions during this period, such as the flying shuttle and the spinning jenny, were not appreciated by workers whose jobs were displaced. These inventions, however, were forerunners of the Industrial Revolution.

OVERVIEW

The Enlightenment and the Industrial Revolution

The term *Enlightenment* was coined to reflect a change in the philosophical approach from that of the preceding ages in which faith in God or faith in classical authors was preeminent. During the Enlightenment, there was a critical examination of previous beliefs in the light of rationalism. The period of the Enlightenment is often equated with the latter part of the eighteenth century, starting with the works of Gotthold Ephraim Lessing (1729-1781) in Germany and Denis Diderot (1713-1784) in France, but this book is divided on the basis of scientific eras. Therefore, the next period begins with the Linnaean classification scheme, which represents scientifically the sense of order that characterized eighteenth-century thought, and terminates just before the publication of the discovery of electromagnetism by Hans Christian Oersted in 1820. In England, the period from about 1740 to 1780 is the time generally considered the Industrial Revolution (*see* "When was the Industrial Revolution?," p 192) which took place somewhat later in other Western nations. Thus, the Enlightenment and the Industrial Revolution overlap considerably.

Philosophy and science

One of the consequences of the revolution in science that took place during the seventeenth century was a profound change in philosophical thinking during the eighteenth century. The success of Isaac Newton's theories, the validity of which became well established during the first decades of the eighteenth century, not only had a profound impact on science itself, but also on philosophical outlook. Newton's success in explaining a large number of phenomena, such as falling bodies and the orbits of planets, by a simple set of laws encouraged people to view the physical sciences as a model for the other sciences. This resulted in the emergence of a "mechanical philosophy;" that is, the belief that not only physics, but also chemistry and biology, could be explained by sets of simple mechanical laws. Most attempts to apply Newtonian mechanics to problems in chemistry and physiology, however, were only partly successful during the eighteenth century.

The idea that mechanics would offer an explanation for all phenomena was taken the furthest by the materialistic philosophers of France such as Denis Diderot, Julien Offray de la Mettrie, and Baron d'Holbach. They denied the existence of a spiritual god, and viewed nature entirely as a mechanical system. In this system, they included humanity itself, body and spirit. They believed that all physiological processes could be reduced to physical processes, but also that spiritual life, social processes, and even the course of history, would fall under the same rules of nature.

Another factor that strongly influenced the philosophical outlook of the eighteenth century was the belief that nature embodied reason, and that the laws of nature would be reasonable laws.

Two approaches to philosophy in the seventeenth century were empiricism—the idea that knowledge comes from experience—and rationalism—the view that knowledge comes from reasoning. A leading philosopher of the eighteenth century was Immanuel Kant, who coined the term "Enlightenment." He reconciled empiricism and rationalism by saying that one can gain knowledge not only from experiences, but also from reasoning—both go hand in hand. The idea of causality—one event causes another to happen—a concept that David Hume rejected for many types of event, became for Kant an *a priori* concept, a general principle that cannot be proved but that has to be accepted as existing independently from our sense perceptions. Space and time, according to Kant, are also *a priori* concepts that are not accessible through the senses, but which condition our sense experiences of the physical world. Therefore, he argued, physics is not a science based only on sense experiences, but also on *a priori* concepts, making it possible to gain knowledge of the physical world using a rational system, such as mathematics.

Another philosophical idea that influenced science at this time had been revived by Gottfried Wilhelm Leibniz, although it had its roots in Plato and Aristotle. The Great Chain of Being, as this idea came to be known, envisioned all existence as continuous. For animals, for example, there

1735-1819

was a continuous chain from the smallest protist to humanity, with no gaps. Some scientists of the Enlightenment, such as comte de Buffon and Charles Bonnet used this notion in their systems of classification, with Bonnet arguing that minerals graded into fossils which were continuous with plants that, somewhere in the vicinity of the green hydra, became animals. At the end of this century, Jean-Baptiste Lamarck used this concept in his theory of evolution. Not all scientists of the period accepted the Great Chain of Being. Georges Cuvier explicitly rejected it, for example.

Over the eighteenth century, this Great Chain of Being also was gradually modified to include the concept of progress—that as time went on, higher beings arose. Various early theories of evolution reflected this notion as well.

The *Encyclopédie*

The flagship publication of the Enlightenment was the *Encyclopédie*. Edited by Denis Diderot and Jean le Rond d'Alembert, the seventeen volumes of text and eleven of illustrations were published from 1751 to 1772. The *Encyclopédie* became important in the democratization of scientific knowledge. Technology was given equal importance to pure science or philosophy. The *Encyclopédie* allowed the philosophers of the Enlightenment to communicate their ideas to a broader public. In keeping with the trend toward systematizing knowledge, another aim of the editors was to lay the foundations of all the arts and sciences. Unlike earlier encyclopedias, such as Ephraim Chambers *Cyclopedia*, on which the *Encyclopédie* was based, the *Encyclopédie* adopted a strong editorial point of view, opposing both church and state.

The romantic reaction

The extreme materialism of some of the thinkers of the Enlightenment bothered many, and toward the end of the eighteenth century a new school of thought, often viewed as a romantic reaction to the materialism and rationalism of the philosophers of the Enlightenment, emerged in Germany: the school of *Naturphilosophie*. There was a similar reaction, generally called romanticism, in both France and England, The most prominent representatives of the *Naturphilosophie* school were the German poet and writer Johann Wolfgang von Goethe, who had also done considerable scientific work, Friedrich von Schiller, the philosopher Friedrich Wilhelm Joseph von Schelling, and the biologist Lorenz Oken. Instead of reason they preferred sentiment. Their view of nature was, to use a modern term, holistic; that is, they believed that all nature should be viewed as a single organism and imbued with spirit. In France, Jean-Jacques Rousseau had expressed similar ideas somewhat earlier, especially in his emphasis upon the importance of emotion.

In both France and the United States, political revolutions and the resulting new governments were heavily influenced by the philosophical trends of the time. Among the revolutionaries in the United States were the parttime scientists Benjamin Franklin and Thomas Jefferson; the French scientists Joseph-Louis Lagrange and Pierre-Simon Laplace held posts in the revolutionary French government. In France even more than in the United States, there was an effort to remake the culture along "scientific lines," including a short-lived reworking of the calendar and the creation of the metric system.

The Industrial Revolution

During the eighteenth century there was a general turn toward the development of machines that would make work faster or more efficient, especially in England. The motive for this surge of inventiveness is not completely clear. Some changes, such as the turn to coal for both heating and making iron, were caused by limitations in natural resources—in this case, wood. Trade certainly was a factor, for example the introduction of cotton from India and the United States. A new class, the capitalists, who were not really the same as the landowners, began to appear. They first bankrolled cottage industry, but soon found it more practical to set up factories. For these and probably other reasons, the Industrial Revolution started. Because of its success in England, it was quickly taken up in those nations that were similar to England; that is, in Europe, the United States, and Canada.

Influenced by technological developments, the Industrial Revolution in turn affected science. Interest in thermodynamics rose as a result of the steam engine. Such concepts as work and power began to be formalized, although this occurred mainly in the nineteenth century. A chemical industry based on chemical processes and not on such organic processes as fermentation slowly started. There was not much effect on life sciences, but industrialization did bring some new medical problems, mainly those connected with the workplace or with crowding.

Major advances

Astronomy. Astronomy profited enormously from Newton's theory of gravitation, from advances made in mathematics, and from the much higher accuracy of reflecting telescopes. Astronomers predicted many astronomical phenomena with great precision. Pierre-Simon Laplace, often called the "French Newton," solved many mechanical problems and demonstrated the stability of the solar system. Astronomers and philosophers abandoned the Aristotelian idea that everything in the universe is static; that is, that since its creation, the universe always has looked the way it looks now. Kant and Laplace introduced the concept of the evolution of the universe and independently formulated a theory, known as the nebular hypothesis, for the origin of the solar system.

The better and more accurate telescopes led to the improvement of positional astronomy, the study of double stars, and the discovery of Uranus and several new planetary satellites. William Herschel was the first to propose that the sun is a star belonging to a vast system of stars, now known as the Milky Way galaxy. By counting the stars in different directions, he tried to determine the shape of the galaxy and found that it must be shaped like a millstone with the sun at its center. Although Herschel was wrong about the details (we now think the Milky Way galaxy is shaped like a spiral with the sun far from the center), the basic idea of the sun's belonging to a vast system of stars was right. Kant suggested that the many patchy objects visible in the telescope may be systems similar to the sun's star system, an idea that was confirmed early in the twentieth century.

The taming of the longitude

The Phoenicians were the world's first great navigators. They determined the location of their ships in terms of the length and width of the Mediterranean, the sea on which they sailed. The Phoenicians taught their navigational methods to the Greeks, from whom the Romans learned. Eventually translated into Latin, the sailors' two perpendicular directions became the longitude (*longus,* or long) and latitude (*latus,* or wide). Eratosthenes drew a map of the known world around the third century BC that included lines of latitude and longitude, but his lines were determined by large cities; that is, they were not equally spaced. In the second century BC Hipparchus of Nicaea greatly improved on this by spacing the lines equally around the globe. By assigning 360° to the circumference of Earth, and by using Eratosthenes' nearly correct calculation for the size of Earth, Hipparchus was able to obtain good distances for a degree. Hipparchus's system continues in use today.

Sailors of classical times, however, used only half the system—the latitude. Early travelers observed the changes in the constellations as one travels north or south. One star, Polaris, is visible every clear night in the Northern Hemisphere, but its position dips closer to the horizon as one travels south. At the North Pole, Polaris is directly overhead, and it disappears below the horizon at the equator. Until sailors began to travel in the Southern Hemisphere, all that was needed to find the latitude was an instrument for measuring how high Polaris, the pole star, was above the horizon. The Portuguese sailors who rounded the Cape of Good Hope were terrified because they had lost their main navigational tool on the trip down the side of Africa.

Sailors did not use the longitude because they had no way to measure it. The historian of Magellan's circumnavigation reported that Magellan himself spent long hours trying to find ways to measure the longitude, but those under him were too proud of their navigational skills to speak of it. Common sailors and their pilots believed that they could navigate by a combination of charts, dead reckoning, and the latitude. Governments, however, realized that this was not good enough. The governmental view was particularly brought home to the English when in 1691 and again in 1707 large parts of the British Navy were lost because of navigational errors.

Much earlier, in 1598, Philip III of Spain offered the first of several prizes by sea-going nations for the person who could find the longitude. Among the schemes suggested to Philip was one from Galileo. Having discovered the four largest satellites of Jupiter, he proposed that they could be used to locate the longitude. Galileo's idea was based using charts that show the relative positions of the satellites at different times. By observing the positions, one can determine the time. From the time, one can find the latitude. By telling the time exactly, one can determine the longitude.

As a clock is carried from place to place, it will be off by one hour for each 15° of longitude. This is why there are four time zones in the lower 48 states of the United States. This part of the United States is approximately 4 × 15 or 60° of longitude wide. Comparing universal time with local time helps one to obtain the longitude. Local noon can be obtained easily, by determining when the sun reaches its daily zenith. It is universal time that is hard to obtain.

The taming of the longitude (continued)

For example, if you get a long-distance phone call from someone while you are in New York City and you do not know where your friend is calling from, you can ask "What time is it?" If it is noon in New York, and your friend says 11 AM, then you know your friend's longitude is approximately between 90° W and 107° W, the approximate longitude of Central Time in the United States. To determine the *exact* longitude, however, you need to forget about time zones and compare sun times between two places. Specifically, compare local sun time with Greenwich Mean Time (GMT), the time at longitude 0°. If you know it is 1:00 PM GMT and you observe the sun time where you are to be noon, your longitude is exactly 15° W.

Astronomical events that repeat frequently are a good way to obtain universal time. Eclipses of the moon could be used, for example, if they were not too infrequent to be of much use to sailors. The positions of Jupiter's moons are more useful because one or another is frequently eclipsed.

Galileo's suggestion was a good one. While ignored by Philip, it was taken up in the seventeenth century by French astronomers, led by Giovanni Domenico (Jean-Dominique) Cassini. Using Jupiter's moons, the French were able to establish correctly the longitude of cities in Europe and of islands in the Atlantic. The observations required, however, were too difficult and too time-consuming to be done by sailors at sea.

In 1530, Gemma Frisius suggested that the easy way to solve the problem would be to carry a good clock, set to some universal time, with the ship. Others had the same idea, but the clocks were not good enough. Even after Huygens developed a pendulum clock that theoretically kept good time, it was too imprecise to find the longitude and too delicate to be used on ships.

Christopher Columbus noted on his first voyage that the compass needle changed its deviation from true north as he sailed across the Atlantic. Many expeditions were launched in the eighteenth century—notably that of Edmund Halley—to chart these magnetic deviations in the hopes that they would lead to the secret of the longitude. It was discovered, however, that the deviations varied in such an unpredictable manner that they were unsuitable for this purpose.

In 1714, the English Parliament provided a reward of £20,000 for anyone who could find the longitude and demonstrate the method on a voyage to the West Indies. Many of the leading scientists of the eighteenth century worked on the problem in competition for the prize, but the achievement was accomplished by a self-taught watchmaker, John Harrison. His clock—or marine chronometer, as it came to be called—Number Four made the West Indies trip in 1761 and passed the test with flying colors. All along the way Harrison's son, who was in charge of the chronometer, predicted landfalls with greater accuracy by far than the ship's pilots. Unfortunately for Harrison, the board governing the prize included a number of scientists who still hoped to get the money themselves. They gave him half the prize after four years, and then stalled him again for seven more years; they would probably have stalled longer if King George III had not intervened on Harrison's behalf.

Biology. During the eighteenth century the classification of plants and animals was still viewed as part of "natural history," a science that also included the study of minerals, for example. Plant and animal physiology belonged to physics. In the *Encyclopédie,* zoology, botany, and medicine were categorized as fields of physics and came under the general heading of "reason." The approach to physiology was consequently mechanistic.

Carolus Linnaeus began the modern system of classification of living organisms and introduced the binary notation system for naming species that is still in use today. Comte de Buffon disagreed with Linnaeus's system of classification because he did not believe that a system based on external characteristics could be a natural system of classification. Buffon proposed a system based on the reproductive history of organisms instead. He said, for example, that a fox is a different species from a dog if and only if it can be shown that matings between a fox and a dog either produced no offspring or (as in matings between a mare and a jackass) sterile offspring.

Toward the end of this period, Georges Cuvier began to classify extinct species. Jean-Baptiste Lamarck studied in detail the anatomy of invertebrates. Both of these men contributed to the concepts that would lead to the theory of evolution in the nineteenth century, although Cuvier did not believe in evolution and Lamarck accounted for it with a now-discredited mechanism (*see* "The theory of evolution," p 275).

Chemistry. During most of the eighteenth century, chemistry was dominated by the erroneous phlogiston theory (*see* "Phlogiston," page 182). A large number of chemists adhered to this theory, which may account for the fact that chemistry advanced at a much slower pace than physics. The scientific revolution that for physics took place during the seventeenth century, happened in chemistry only at the end of the eighteenth century with the work of Antoine-Laurent Lavoisier, Henry Cavendish, and John Dalton. Also, the number of technical applications was relatively small during the eighteenth century. A chemical industry did not flourish until the nineteenth century, when the mechanisms of chemical reactions were more fully understood.

Lavoisier proposed a correct theory of combustion at the end of the eighteenth century, opening the way to the rapid development of chemistry during the early years of the nineteenth century. At that time John Dalton put forth his atomic theory, which eventually became the foundation of the new chemistry.

When was the Industrial Revolution?

The French coined the term *Industrial revolution* in the nineteenth century as an analogy to their own political revolution. Although the phrase is in common use, it is not always clear what this phenomenon was or even when it occurred.

For example, it has been pointed out that humans underwent *an* industrial revolution at the beginning of the Bronze Age; yet, it is clear that *the* Industrial Revolution is something else. One theory holds that the Industrial Revolution happened when people stopped using human and animal power and began using inanimate power sources; this could place the Industrial Revolution as early as the first extensive use of wind and waterpower—medieval times in the West and somewhat earlier in China. A different suggestion is that it began when mills began to centralize the production of textiles. This might be interpreted as occurring when fulling mills (mills to work cloth so that it is fuller) began, in the thirteenth century. Perhaps the date ought to be tied to the large-scale production of iron in blast furnaces, which employed workers in something like a factory system. That postpones the revolution to the fifteenth and sixteenth centuries. Or maybe it started with the first factory, probably the six-story English silk-thread mill built in 1719 that employed 300 workers, mostly women and children.

A few years after that first factory, John Kay made one of the key inventions that started what we think of today as *the* Industrial Revolution: the flying shuttle, which made weaving much faster. And a few years before that factory, Abraham Darby discovered how to make steel using coal instead of wood—actually, coke instead of charcoal. This allowed for a greater output of cheap steel, since coal was more plentiful than wood at that time in England.

The problem with these early eighteenth-century inventions is that no one took them up. It was over 50 years before other steel makers started following Darby's example; and weavers afraid of losing their jobs destroyed Kay's loom and sent him packing to France.

About 1750, however, cotton workers, with less of a tradition behind them than the wool workers who attacked Kay's loom, started using the flying shuttle. This set into motion a chain of events that revolutionized the textile industry. With the flying shuttle, cotton workers were able to weave so much faster that they ran out of yarn. Seeing an opportunity, James Hargreaves invented a machine that multiplied the amount of yarn produced, the spinning jenny. This time the spinners were upset, and they destroyed some of Hargreaves's machines, but the cat was out of the bag. The spinning jenny could make only one of the two types of yarn needed for weaving. Richard Arkwright also saw opportunity knocking: he invented the water frame, a machine that produced the other type of yarn. Unlike the spinning jenny, the water frame was too large and too expensive to put in a cottage. Arkwright had to build a factory to house his machine; he is, in fact, considered the founder of the modern factory system. By 1769 the Industrial Revolution had definitely begun; many date the start back to the 1740s when the cotton weavers first adopted the flying shuttle.

However, there is another key invention that is not yet in place in 1769. Since at least 1629, when Giovanni Branca suggested using steam to propel a turbine, people had been experimenting with steam power. Branca was followed by the Marquis of Worcester in England, Denis Papin in France, and, in England again, Thomas Savery. Savery, at the very end of the seventeenth century, was the first to make a practical steam engine, known as "the Miner's Friend." It wasn't very efficient, however, and only a few were installed. Soon Thomas Newcomen recognized the opportunity, and developed a greatly improved steam engine that was more along the lines of the modern engine. Newcomen then got together with Savery, and the new engine was successfully manufactured and sold to drain mines. Over 100 Newcomen engines were installed during the eighteenth century. An engineer at Glasgow University, James Watt, in 1765 developed a new device, the steam condenser, that greatly improved the efficiency of the Newcomen engine. Ten years later, Watt teamed with a manufacturer of iron products, Matthew Boulton of of Birmingham, to manufacture his new engine. Boulton had access to the technology needed to make finely machined parts that gave the Watt engine greater efficiency and durability. Boulton also convinced Watt in 1781 to convert the engine from a simple pump to a device producing rotary power—the first steam engine that could power other machinery. Four year later the first steam-powered cotton mill opened in Papplewick, Nottinghamshire. By this date, the revolution part of the Industrial Revolution in England had been completed. It would occur 30 years later in France and 20 years after that in Germany and the United States. Assigning the revolution a single date would be misleading. It took from the 1740s until the 1780s; after that, came consolidation of power by the revolutionaries.

Earth science. One of the results of the Industrial Revolution was an increase in prospecting for coal and ores. This stimulated interest in the study of fossils and rocks, giving birth to a new science, termed "geology" by Horace de Saussure. Until the middle of the eighteenth century, it was generally believed that fossils and rocks were deposited by Noah's flood, which, it was thought, had covered the whole planet. This was despite the fact that Robert Hooke had already shown that it was not possible that the thick layers of fossils could have been deposited in the 150 days the flood was believed to have lasted. The French naturalist Buffon believed that Earth was much older—80,000 years instead of 6000 years old. The figure of 6000 years was a value obtained from the Old Testament, however, and was widely accepted (*see* "The age of the Earth," p 404). Buffon also rejected the idea that Noah's flood was responsible for the existence of fossils, but he had to withdraw his writings because of opposition by the church.

Abraham Gottlob Werner, a professor of mineralogy at the Mining Academy of Freiberg, was the first to introduce systematic observation in the science of geology. He showed that rocks were formed layer by layer, with the oldest rocks at the bottom and the youngest ones on top. He argued that in the past Earth's surface was covered by a muddy sea and that Earth's crust was formed by deposition of suspended material. The crystalline rocks, such as granite or basalt, were, according to him, formed by the precipitation of minerals. His theory, called the *Neptunist* theory, was opposed by the *Vulcanists,* who argued that the layers of rock in Earth's surface were formed exclusively by volcanic action, and the *Plutonists,* who emphasized the importance of heat from within Earth. James Hutton, who believed that some rocks were formed by volcanic action, also accepted sedimentation as a rock-forming process. His major contribution to geology was the insight that the surface of Earth was formed by the same forces that still are active today—mainly erosion and volcanism (*see* "Neptunism vs. Plutonism," p 234).

Mathematics. The introduction of calculus by Newton and Gottfried Wilhelm Leibniz had caused mathematics to develop rapidly into a tool eminently suited for dealing with problems of theoretical mechanics. The notations of Leibniz and those used by Leonhard Euler were accepted in continental Europe. In England Newton's notation was used throughout this period (*see* "Inventing signs," page 94). The wholesale application of calculus to physical problems, initiated by the Bernoulli brothers early in the eighteenth century, was continued by Euler, d'Alembert, and Lagrange. Euler and Lagrange created the calculus of variations. Lagrange introduced the differential equations now called Lagrangians, which could be used to represent Newton's laws of motion in a more generalized form. Laplace applied Newton's theory of gravitation and calculus to astronomy in detail, furthering the field of celestial mechanics. A new mathematical field, statistics, initially developed by Jacques Bernoulli, was further refined by Abraham De Moivre and Laplace.

Medicine. Several important developments occurred in the medical sciences. A significant advance in physiology was the publication of Albrecht von Haller's medical encyclopedia, *Elementa physiologiae,* started in 1757. This was the beginning of modern physiology as an independent science. François-Xavier Bichat founded histology—the study of tissues of living things—around 1800. Edward Jenner introduced vaccination to prevent smallpox at the end of the eighteenth century, the first successful method in medicine for fighting disease on a large scale.

Physics. The developments in the science of mechanics were mainly the result of advances in mathematics. Newton's physics was finally accepted in France because it successfully predicted that Earth would be flattened at the poles and also correctly predicted the return of Halley's comet.

However, Newton's physics could only treat problems in which all the mass of a body is viewed as concentrated in one point, the center of gravity. Such a limitation is acceptable for the calculation of planetary orbits, but not useful in many other cases. Leonhard Euler first introduced the generalized coordinates of a body, a mathematical system that allows the whole motion of an extended system, such as a pair of scissors flying through space, to be analyzed. The individual motions of each half of the scissors could be accounted for instead of just the motion of the center of gravity of the scissors. Lagrange improved on Euler's coordinate system so that it could be applied to systems of several moving bodies taken all at once. He also gave a proof that the principle of least action (for example, that the kinetic energy takes on a minimum value when bodies are left moving freely) could be derived from Newton's laws of motion.

Count Rumford cast doubt on the commonly accepted solution to a problem that had intrigued scientists throughout the century: the nature of heat. Heat was generally viewed as a kind of fluid by most eighteenth-century scientists. Rumford measured the amount of heat produced by boring a cannon, which was enormous. He did not think that the cannon could contain so much caloric, the purported fluid. Instead, since heat was being produced by motion, he suggested heat is a form of motion itself (*see* "The nature of heat," p 320). Although he failed to convince many then, later studies showed that he was right.

The eighteenth century was also a period of extensive experimentation with electricity, although the nature of electricity remained largely a mystery.

Technology. During the eighteenth century technology in the modern sense of the word appeared: the direct application of science to machines. The introduction of the steam engine had an enormous influence on science as well as on manufacture and transportation. The improvement of steam engines was based on the science of gases that developed during the late seventeenth century and later on the development of the theory of heat. Engineers started measuring the efficiency of machines using scientific principles: the assessment of machines became a quantitative science.

At the same time, there was a lot of pure invention by amateurs. The people who remade the textile industry during this period were not scientists, but they certainly were inventors. Near the end of the period, the American inventor Eli Whitney introduced standardized parts into technology, providing a major change in the way products are manufactured.

It was generally understood that the teaching of science and technology is an important part of the technological development of a country, and several engineering schools were established throughout Europe. The Ecole Polytechnique in Paris, founded in 1794, became an important source of talent for the development of science in France during the nineteenth century.

OVERVIEW

Nineteenth-century science

Scientists in the eighteenth century had become increasingly fascinated with electricity, especially as better means of generating and storing it became available. Their work culminated in the Voltaic pile, or battery, in 1800. Before this invention, electricity was only available for the brief moment of a discharge or as small amounts of static electricity. After 1800, scientists could work with an electric current. Even so, there was little progress toward understanding the nature of electricity until Hans Christian Oersted's accidental discovery, published in 1820, that electricity and magnetism are linked. As soon as word of this discovery spread, André-Marie Ampère, François Arago, and Michael Faraday began both to explain electricity and to try to put it to practical use. Indeed, Faraday had built the first prototype of the electric motor by 1821 and the first form of electric generator ten years later. It was not until late in the century, however, that practical applications became possible.

Much nineteenth-century science started with the discovery of electromagnetism, including Maxwell's mathematical laws that describe it (possibly the high point of nineteenth-century physical science), and from the relationship of electrolysis to chemistry. As the twentieth century dawned, the more developed nations were utilizing the technological results of this scientific effort: electric motors, electric lights, the telegraph and telephone, the radio, and many other milestones.

At the end of the century, work with cathode-ray tubes led directly to the discovery of X rays and the electron and indirectly to the discovery of natural radioactivity. The passage from electricity to electrons—or from Oersted and Volta in 1820 to Wilhelm Konrad Roentgen, J.J. Thomson, and Antoine Becquerel from 1895 to 1897—marks the true beginning of twentieth-century science. The new era begins with the surprises of 1895.

The nature of science

The nineteenth century was a period in which science and the teaching of science underwent a number of changes, giving it much of the form it has today. Science expanded enormously during the period and many of the new fields of science, such as anthropology, archaeology, cell biology, psychology, and organic chemistry originated during the first half of the century. Many other sciences, such as geology and chemistry, matured during the period.

During the eighteenth century, scientists who were not wealthy had to depend largely on patrons. There were no institutions that supported scientists, although there were a few teaching jobs and a little money could be made from books. This situation changed during the nineteenth century as the occupation of scientist became a paid profession. This development first took place in Germany, where in a few decades the universities developed into centers where science flourished. Justus von Liebig set up his research laboratory for chemistry at the University of Giessen, initiating a trend that was soon followed at the other universities. The teaching of science became linked to scientific research, a practice that later was followed by most of the universities in the world. The universities and scientific societies also started publishing scientific information, a development that was imitated in other countries. Scientific papers became important. In Germany, with Lorenz Oken taking the lead, scientists started meeting at national scientific congresses from 1822 on. First viewed with suspicion, these congresses later became instruments for increasing national unity in Germany.

Science continued to be truly international in this century. During the Napoleonic wars at the beginning of the century, scientists could freely travel between France and Britain. During the second half of the century, scientists started to travel to international conferences. The exchange of scientific information between nations increased considerably.

France was the leading scientific country during the first decades of the nineteenth century, mainly through the impetus of Napoleon and the influence of the Ecole Polytechnique, the breeding ground for much scientific talent. In Germany during the eighteenth century, science was much less developed than in France or England and was still strongly influenced by mystical concepts from the Middle Ages and the Renaissance. Many of the great German scientists had to leave Germany for their education: Friedrich Wöhler went to Sweden to study with Jöns Jakob Berzelius, and Liebig went to Paris to study with Joseph-Louis Gay-Lussac.

Wilhelm von Humboldt, director of the Prussian Department of Education and brother of Alexander von Humboldt, started the reorganization of higher education in Germany and founded the Berlin University in 1809. This university soon became the model of the other universities throughout Prussia. While the French universities were closed during the revolution and their replacements began to suffer from the French bureaucracy, teaching at German universities became more liberalized. Although the German universities were state controlled, the concept of academic freedom, the freedom of professors and students to choose their topics of study and research, became important and contributed to the strong development of science in Germany. The German term for science, *Wissenschaft,* is a broad term that includes all systematic knowledge, such as philosophy, philology, and history. This broad view encouraged an exchange among different scientific disciplines and also the development of entirely new fields, such as psychology.

National differences in style of research

During the nineteenth century differences in style of research between countries became fully apparent. In Germany, where science was strongly organized, the university system favored pure science; in England scientists traditionally dealt with practical problems.

The research style in England was similar to that of the eighteenth century and the number of scientists stayed relatively small. Science was the domain of a few talented individuals. Many scientists had no academic positions. Training in science was generally lacking in England, although a large number of amateur associations of scientists existed. Several technical schools ("mechanic's institutes") were founded around the middle of the century. In some of them science teaching was more advanced than at the universities of Oxford or Cambridge, hampered by their connection to the Church of England, which required (in theory at least) that instructors be clergymen and that dissections not be practiced.

In England, the Analytical Society began a trend toward reviving mathematics that culminated in the start of abstract algebra before the end of the century. Started by undergraduates at Cambridge, the society was committed to bringing Continental mathematics to England. They recognized that almost no one in England could read or understand Continental mathematics, in part because the symbolism used was not the same.

In Scotland the situation was somewhat different. The University of Edinburgh was not connected to the church; consequently, it was free to develop a medical school that became central to the scientific enterprise throughout Great Britain (*see* "The Lunar Society," p 216). Aspiring to a national identity, the Scottish universities developed quickly and established a tradition for learning that is still strong today. The Scottish universities attracted large numbers of students studying chemistry, but as professors' income were based on the number of students attending courses, the transition to practical classes and scientific research was never made.

Interest in science grew in England throughout the century. By the end of the century, there were about a hundred times as many people enrolled in the various English scientific societies as there had been in the single Royal Society of the preceding century.

In the United States, relatively little attention was given to science. The population in the United States grew steadily because of immigration, but the interests of the immigrants were largely oriented toward practical ventures rather than the pursuit of theoretical knowledge. The country excelled, however, in technology. Labor-saving devices were especially valued because of the comparatively low population density and the resulting high salaries for manual workers. Therefore the role of technological inventors and entrepreneurs in industrial development was large: many major US industries were founded by inventors such as Alexander Graham Bell, George Westinghouse, Thomas Edison, and George Eastman. In 1848 the

Although the ancient Greeks and probably earlier peoples knew about magnetism and static electricity, not much was accomplished with these interesting phenomena until the Chinese began to use the magnetic compass for navigation around 1000 AD. Some of the basic laws of magnets were written down in 1269 and William Gilbert studied both static electricity and magnetism at the end of the sixteenth century. Then the subject was ignored by most scientists for a long time.

In the eighteenth century, Stephen Grey and Charles François Du Fay revived the study of static electricity, but it was not until Pieter van Musschenbroek received the first known electric shock (apart from those caused by lightning) in 1745 that the subject gained attention. Van Musschenbroek was one of the inventors of the Leiden jar, a device for storing static electricity. A Leiden jar releases all of its electricity at once, causing a shock if it passes through a grounded person. Van Musschenbroek reported, "In a word, I thought it was all up with me" after his shocking experience. The discovery that electricity could cause shocks prompted Benjamin Franklin's famous kite experiment, in which he showed that lightning is electricity. It could have been "all up with" Franklin during that experiment too. Other scientists who repeated the experiment were killed.

Charles-Augustin Coulomb made careful studies of the forces exerted by both static electricity and magnetism in the 1780s. As early as 1733, Du Fay had discovered that there are two types of charge and that like charges repel while unlike charges attract. Coulomb showed that both magnets and electric charges obey the same rule, an inverse-square law. This implied a connection between electricity and magnetism. In 1807 Hans Christian Oersted announced that he would search for that connection.

Somewhat before this, there had been a major development in electricity that would facilitate Oersted's search. In 1791, while studying the reactions of muscle to electricity, Luigi Galvani accidentally discovered that the muscles behaved as if a current was passing through them when they were placed in contact with brass and iron at the same time. Although Galvani thought the muscles were the sources of the current, when Alessandro Volta learned of this phenomenon, he found that a simple chemical solution could be substituted for the muscles. With this knowledge, he cleverly constructed the first electric battery at the end of the eighteenth century. The battery was the first source of current electricity, electricity that moves steadily through a conductor as opposed to being quickly released from a Leiden jar.

The history of science is replete with stories of someone finding something by luck or accident. What is often overlooked in these tales is that the scientist in question had already been looking for something like the phenomenon he or she "accidentally" discovered. If Galvani had not been studying electric actions on muscle, he would not have been prepared to notice the reaction of the muscle with the metals. Similarly, Oersted discovered the connection he sought by accident while he was performing a classroom demonstration. He placed a compass over a wire carrying a current. As he did, the needle suddenly moved to become perpendicular to the current. Electricity and magnetism really were connected.

As soon as Oersted's discovery became known in 1820, there was a burst of creative activity. In 1820 alone, André-Marie Ampére and Dominique Arago discovered that wires carrying currents attract or repel each other and that an electric current in a wire will attract iron, just as a magnet does. Three years later the thermoelectric effect was discovered by Thomas Seebeck. Also at that time, William Sturgeon built the first electromagnet.

A notable series of investigations of the relationship between electricity and magnetism was conducted almost in parallel in England by Michael Faraday and in America by Joseph Henry. Both Faraday and Henry discovered the principle of the dynamo in 1830–1831, for example. Although they independently discovered many of the same connections and devices, Faraday's work was to have the greater theoretical impact while Henry's had more immediately practical application.

Faraday had observed how iron filings form patterns of lines under the influence of a magnet and similar phenomena. He concluded that space is filled with these invisible lines, forming what we now call a field. He used his idea to explain in 1845 why some substances are diamagnetic (developing a magnetic field opposite to the one surrounding them) and others paramagnetic (developing a magnetic field parallel to the one surrounding them). When Faraday discovered that a magnetic field can affect the polarization of light, he proposed in 1846 that light may be waves in the lines of force of electromagnetism.

There were other clues to a relationship between light and electromagnetism. In 1857, for example, Gustav Robert Kirchhoff calculated the relationship between the forces of static electricity and magnetism, finding that the speed of light in a vacuum is a constant in his formula. In 1864, James Clerk Maxwell followed up Faraday's ideas with mathematical formulas that described light as waves of electromagnetism and that implied other forms of electromagnetic waves. Maxwell's work was experimentally verified in 1888 when Heinrich Hertz, following a suggestion from George Francis Fitzgerald, discovered radio waves by directly applying Maxwell's formulas.

In America, Henry developed the first practical electric motor and powerful electromagnets in 1831. In the 1830s he also developed the electrical relay that made the first practical telegraph possible. Samuel Finley Breese Morse, usually given credit for the telegraph, worked directly with Henry and incorporated his ideas into the new device.

In 1879 Thomas Alva Edison and Joseph Swan independently invented practical lights that use electricity. With this invention, electricity moved into the home, where the many discoveries of the nineteenth century soon found application.

American Association for the Advancement of Science was founded; it played an important role in the development of American science. But theoretical science remained in a secondary role in American education until well into the twentieth century.

The philosophical basis of nineteenth-century science

During the beginning of the nineteenth century, especially in Germany, there was a romantic reaction against the mechanistic and materialistic philosophy behind scientific development. The influence of Hegel, whose philosophy of nature was not based on experimentation but on *a priori* concepts, remained strong throughout the first half of the century in Germany. Scientists such as the great German poet Johann Wolfgang von Goethe tried to find scientific explanations by using general philosophical principles. For example, Goethe fought Isaac Newton's idea of white light as a mixture of colors, claiming that in principle white light should be simpler and purer in composition than colored light.

The idea that science would ultimately explain all phenomena in nature became stronger. The *Naturphilosophie* eventually lost influence and was replaced by materialism: *Kraft und Stoff* (force and matter) became the tenet of the new philosophical outlook. Matter and force, and later, matter and motion, were viewed as the ultimate explanations of reality.

The French philosopher Auguste Comte became the strongest spokesman of the philosophical school termed "positivism." He viewed science as the most advanced stage of knowledge. In positivism the use of scientific principles to explain the laws governing all phenomena supersedes the two earlier stages of knowledge: a theological or imaginative stage in which phenomena are explained by divine powers, and a metaphysical or abstract stage in which phenomena are explained by general philosophical ideas.

Science and the public

Scientific thought was not only much better known, but for the first time it was opposed by segments of the public, especially those who held certain religious beliefs. This reaction was different from the official condemnation of Galileo by the church, which was essentially an institutional response, or Bishop George Berkeley's criticism of Newton and Edmund Halley. It also had little in common with the popular reaction against labor-saving technology of the eighteenth century. The nineteenth century saw general public criticism of some scientific ideas, along with newspaper cartoons and well-attended public meetings.

The first issue to cause this kind of problem was the age of the Earth (*see* "The age of the Earth," p 404). Geologists offered good evidence that Earth is far older than most Christians, Jews, and Moslems believed (at the time, about 6000 years, because 6000 years easily encompasses all the events of the Bible). Although Buddhists and Hindus believed Earth to be far older, they were not influential in science at the time. Opposition in this case was not so much the organized opposition of the church, as was the case when the Copernican theory was championed by Galileo, but rather the refusal at the level of the ordinary minister or churchgoer to accept the concept of an older Earth.

Opposition to this idea, however, was muted compared to the great reaction against Charles Darwin and Alfred Wallace's theory of evolution by natural selection. People did not want to admit that humans were descendants, however long ago, of animals. The popular conception—never advocated by scientists—that human ancestors were monkeys was particularly the subject for ridicule. This controversy has continued to agitate some religious groups in the United States throughout the twentieth century, although in the rest of the world it was settled in favor of evolution by the end of the nineteenth century.

Science and technology

At the end of the eighteenth century, discoveries by Antoine Lavoisier and Nicolas Leblanc in France had propelled a small chemical industry. But it was in Germany, which became the leading country in theoretical chemistry, that chemical research had the biggest impact on industry. By the end of the nineteenth century, the country had developed into the largest manufacturer of such chemicals as dyes, fertilizers, and acids used in industrial processes.

The relationship between scientific education and technological progress became fully understood during the nineteenth century. Following the example of the Ecole Polytechnique in France, Germany, and later the United States, also founded technical schools with the idea of applying science to technology. At the end of the century, these technical universities played an essential role in the rapid expansion of Germany's industry. They developed the various kinds of engineers who used science to solve technological problems rather than to advance knowledge.

The scientific method

In Cambridge in 1883, William Whewell suggested to the British Association for the Advancement of Science that their members be called scientists, a term analagous to the word artist for those who practice the arts. Today we would call few of those members scientists, since most were amateurs or supporters of science. The word gradually caught on, however, and began to displace "natural philosopher, although many of the scientists of the nineteenth century resented Whewell's new terminology.

Gradually, during the course of the century, the concept of a scientist became codified, at least in the public mind. The scientist observes, forms a hypothesis, conducts an experiment to test it, and announces a theory. In practice, most science has never been conducted according to this strict "scientific method." Some scientists never conduct experiments, while others determine many facts by experiment and never produce a theory.

Part of the development of the concept of a scientific method resulted from a change during the century in how students learned science. Laboratories were set up at the University of Edinburgh and, later, at other universities. William Thomson (later Lord Kelvin) was the first to have his physics students at the University of Glasgow conduct experiments.

Major advances

Anthropology and archaeology. Interest in archaeology, spurred in the second half of the eighteenth century by the excavation of Pompeii, increased after Napoleon's expedition to Egypt in 1798. Napoleon took scholars with him to study the antiquities known to be there. One of their discoveries, the Rosetta stone, proved to be a seminal object. Jean Champollion in 1822 recognized that the stone contained the same inscription in two Greek scripts and in Egyptian hieroglyphics and was able to translate the previously untranslatable Egyptian inscriptions. Soon after, Georg Friedrich Grotefend and Henry Rawlinson translated the first texts in the cuneiform system used in Mesopotamia. Around the same time (1839), John Lloyd Stephens and Frederick Catherwood discovered the Maya civilization, the beginning of serious archaeology in the New World.

The most notable excavation of the century was the unearthing of many previously unknown tombs and temples in Egypt. Also notable was the discovery that the mounds of Iraq were actually such fabled cities of Mesopotamia as Nineveh and Ur. The most surprising find was Hermann Schliemann's excavation of Troy, which he followed with locating the ruins of the Mycenaean civilization.

In the New World, E. George Squier moved from surveying the mounds of the Mississippi valley in the 1840s, to Central America in the 1850s, and finally to Peru in the 1870s, discovering previously unknown civilizations all

Non-Euclidean geometry

Even in Hellenistic times, Euclid's fifth postulate was viewed suspiciously. Euclid himself arranged his *Elements* so that the fifth postulate was not used in the first 25 propositions, although the 16th assumes something equivalent to it. The suspect postulate was much more complex and less self-intuitive than the other postulates, which are in the nature of, "through two distinct points one and only one straight line can be drawn." The fifth postulate states, "If a straight line falling on two straight lines makes the interior angles on the same side less than two right angles, the two straight lines if produced indefinitely meet on that side on which are the angles less than the two right angles." One objection to the fifth postulate was that the meeting point could be as far as one liked from the original line; in essence, the point could be infinitely far away. By the time of Proclus, 750 years after Euclid, geometers were bent on getting rid of this objectionable postulate—but no one could figure out how.

There were essentially two strategies used: replacing the fifth postulate with a different equivalent postulate or establishing it as a mere theorem, a result proved from the other postulates. For the first strategy, the most common version of the postulate used today is known as Playfair's postulate after the eighteenth-century version of British mathematician John Playfair. It states, "Through a given point, not on a given line, only one parallel can be drawn to the given line." Although Playfair's *Elements of geometry* popularized this postulate, Proclus had also used it as an alternative to the fifth postulate in the fifth century AD. Playfair's postulate is a little easier to understand than Euclid's fifth postulate, but because the two postulates are equivalent, it is just as suspect. Two postulates are equivalent when each one implies the other.

The second strategy also involves equivalent postulates. For each time that someone tried to prove the fifth postulate as a theorem, it was found that he had to invoke a result that was equivalent to the fifth postulate. These equivalent postulates include "A line that intersects one of two parallel lines intersects the other"; "The sum of the angles of a triangle is 180°"; "For any triangle there exists a similar triangle not congruent to the first triangle"; and "There exists a circle passing through any three noncollinear points." Invoking any of these in a proof of the fifth postulate amounts to circular reasoning since each is equivalent to the fifth postulate.

In the eighteenth century, Girolamo Saccheri suggested a third strategy, indirect proof of the fifth postulate by contradiction. He assumed that one of the equivalents to the fifth postulate was *not* true. There were two ways in which this equivalent postulate could be not true, so Saccheri needed to deal with two assumptions. Saccheri developed a number of geometric theorems from each of these assumptions combined with Euclid's other postulates, looking for a contradiction between two of these new theorems. Finding such a contradiction from one assumption would mean that either the fifth postulate or the other assumption had to be true. Saccheri convinced himself that he had found such contradictions for both assumptions, leaving the truth of the fifth postulate the only remaining possibility. His report of his efforts was called *Euclid vindicated of every blemish*.

Non-Euclidean geometry (continued)

Other mathematicians agreed that one of the assumptions easily produces contradictory theorems, provided one also assumes that lines are infinite. But to contradict the other assumption, Saccheri struggled. In the process of trying to find the contradictions, he developed a large amount of what we now recognize as a non-Euclidean geometry. Saccheri finally convinced himself that he had found a contradiction using the other assumption, but it rested on some very shaky geometry that other mathematicians rejected.

Although Saccheri is best known for this approach today, his work was not well known in his own time. Other mathematicians, notably Johann Heinrich Lambert and and Adrien-Marie Legendre, also tried the same strategy, with approximately the same results.

When he was 15, Karl Friedrich Gauss began to work on the problem of the fifth postulate. Gauss recapitulated the approaches of others with the same results, except that he was better than they had been at seeing that his attempted proofs did not work. After 25 years of working on the problem, he evidently reached the conclusion that the fifth postulate is independent of the others. This means that a contradiction to the fifth postulate can be used to develop a consistent geometry. Gauss proceeded to do this to his own satisfaction, but did not publish his work, although he told a few friends about his conclusion.

Shortly after (around 1830), two other gifted mathematicians also reached the conclusion that the fifth postulate is independent of the others. Both Nikolai Ivanovich Lobachevski and Janos Bolyai independently discovered and published their non-Euclidean geometries. In all three versions (including that of Gauss), the mathematicians assumed that more than one line passing through the same point could be parallel to another line, which is equivalent to the assumption that gave Saccheri such doubtful results. Although both Lobachevski and Bolyai campaigned for their views, the concept of non-Euclidean geometry had little impact for the next quarter of a century.

In 1854, however, Bernhard Riemann discussed the foundations of geometry in a general way, giving very little mathematical detail, but making non-Euclidean geometry more accessible. Riemann also suggested that there were several non-Euclidean geometries. For example, one could avoid the contradictions of Saccheri's first assumption by changing Euclid's first and second postulates along with the fifth. The result appeared to be consistent—that is, no contradictory theorems can arise.

In short order, Eugenio Beltrami was able to prove that the original non-Euclidean geometry of Lobachevski and Bolyai is consistent if Euclidean geometry is itself consistent. Felix Klein soon showed that two different versions of Riemann's geometry were also as consistent as Euclid's. The method employed in each case was to find a model of the non-Euclidean geometry that was within Euclid's geometry. The easiest such model to understand takes the surface of a sphere as the plane, which is undefined in the modern treatment of Euclidean geometry. Then if great circles are taken to be lines, they obey such postulates as "Two distinct points determine at least one line" (replaces Euclid's first postulate), "A straight line is finite in length" (replaces Euclid's second postulate), and "No two lines are parallel" (replaces Euclid's fifth postulate). The new postulates not only describe one form of non-Euclidean geometry, they also accurately describe geometry on a sphere (with the understanding that a line is really a great circle); but geometry on a sphere can also be described by Euclid's original postulates when great circles are understood as circles, not lines.

Despite the mathematical validity of non-Euclidean geometries, they were not deemed of much practical value until 1915, when Albert Einstein showed that gravity could be explained by treating space as a four-dimensional Riemann-type geometry. In other words, space itself is non-Euclidean, despite our impression of it. This is because we view it on a small scale. On a small scale, Earth looks flat. On a larger scale, with a different definition of line, it is non-Euclidean.

along the way. In the last quarter of the nineteenth century, archaeologists became aware of the civilizations of the American Southwest.

Just as archaeology was being born, another closely related science came into being. Unlike archaeology, which at least had some ancient texts, such as Herodotus, Homer, and the Bible, to guide it, the other new science, anthropology, was starting from scratch. It had occurred to only a few people that human beings might have existed long before any of the known civilizations. When the first Neanderthal remains appeared in 1856, there was no context in which to put them. They were initially interpreted as recent. The peculiarities, or differences from a modern skeleton, were attributed to disease. Then, in 1859, Charles Darwin's theory of evolution provided a theoretical context. Furthermore, Charles Lyell had already offered convincing arguments that the age of Earth was greater than most people thought. There was time for various precursor cultures of human beings to exist. The important 1879 discovery of cave paintings at Altamira in Spain was too spectacular for most people to accept. It was acceptable for early people to make primitive stone tools (after all, American Indians had used stone tools when they were first encountered), it was unacceptable for them to be great artists.

As time passed and Darwin's ideas gained influence, the idea of an ancestor to human beings took hold. For one thing, more Neanderthal remains were discovered, making Neanderthals a likely candidate as a different species of human (although today most scientists consider them a subspecies of the modern human). Furthermore, geological evidence suggested that some clearly human remains might be as old as 35,000 years. Eugène Dubois decided he would look for the "missing link" between people and the great apes. He believed that Java would be a good place to look, so he managed to get a job in Java. Astonishingly, he found the remains of a new species, closely related to modern humans, on the island.

At the end of the nineteenth century, despite these discoveries, physical anthropology was still not much of a science. It would gradually develop in the twentieth century, joined by the even newer science of cultural anthropology.

Astronomy. Progress in the nineteenth century was marked by two technical discoveries that each did something unexpected. One was the discovery that light can be recorded by chemicals (in photographs) and the other was that light from different hot elements is itself different—so that, for example, one can tell the difference between hot hydrogen and hot sodium merely by examining the light each gives off. The first discovery meant that astronomers no longer had to depend on looking through a telescope and recording what they saw in words or drawings. They could, instead, photograph what they saw. The second discovery meant that something that everyone thought to be completely impossible was in fact quite possible: a scientist could determine which elements are in a star. The two important new tools of photography and spectrography were eventually combined, and photography of stellar spectrums was routine by the end of the century.

Ancient astronomers had realized that the stars must be very far away, since they showed no measurable parallax (apparent movement as seen from the opposite ends of Earth's orbit). Indeed, the absence of measurable parallax was used as an argument that Earth does not move. The discovery by Frederich Bessel and others that stars are so far away that light takes years to reach Earth considerably expanded our understanding of the size of the universe.

Other discoveries were closer to home. Mathematics was the key in locating the eighth planet, Neptune, while careful observation at a propitious time helped Asaph Hall find the moons of Mars. An excellent telescope at an excellent location helped Edward Barnard locate the fifth known moon of Jupiter. Since Barnard's discovery in 1892, all subsequent discoveries of planetary satellites have been made using photography or by space probes.

A key change in the way observatories were sited also affected astronomy at the end of the nineteenth century. Before 1887, telescopes were placed wherever it was convenient, usually in the vicinity of major cities. In 1887, the Lick Observatory was built on top of California's Mount Hamilton, an inconvenient place that offered good viewing. Almost every optical observatory built since has been on a mountain top.

Biology. One of the great events in the history of science occurred when Darwin and Wallace presented the theory of evolution to the world in 1858 (*see* "The theory of evolution," p 275). This was the watershed event in biology in the nineteenth century, but there were many other significant discoveries.

One was the development of the cell theory and the understanding of the importance of the chemistry of cells. Schleiden and Schwann proposed the cell theory for plants and animals in 1838-1839. The technique of staining cells allowed biologists to begin to understand how the parts of a cell work.

Louis Pasteur made important advances in chemistry, biology, and medicine, many of them connected to each other. He showed that fermentation is not a purely chemical process, but one that is caused by yeast, and he convinced most biologists that spontaneous generation does not occur.

The borderline between chemistry and life was discovered late in the century as biologists realized that some agents of disease could pass through their finest filters. These unseen and unknown agents came to be known first as filterable viruses and later simply as viruses. Their exact nature would not be known until the twentieth century.

Important advances in understanding heredity occurred during the century, but were not realized at the time. The most significant, Mendel's laws, were published but not noticed. They were rediscovered in 1900 (*see* "A remarkable coincidence," p 396). Progress was also made toward discovering the mechanisms of heredity, but most of this progress can only be recognized in hindsight (*see* "Discovering DNA," p 492).

Chemistry. In some ways, chemistry is the archetypal nineteenth-century science. Chemists of the eighteenth century had paved the way for modern chemistry by ridding themselves of phlogiston, discovering elements, and accepting the atom. In the twentieth century, chemistry would be rethought in terms of physics. In the nineteenth century, however, chemistry held sway as the leading science.

But nineteenth-century chemistry was still emerging, with little understanding of why certain rules worked. For example, the concept of valence was introduced in 1852 and the periodic table in 1869, but it was not until the discovery of Wolfgang Pauli's exclusion principle in 1925 that either of these could be understood from first principles. The same holds true for another major advance, spectroscopy. With no understanding of how electrons behave—indeed, without any suspicion of electrons—the wonder of spectroscopy, identifying elements from the light they give off when heated, emerged without a theoretical basis. Chemistry is not alone in running ahead of its theories. A similar situation existed with gravity, for example; it was an enormously successful concept long before Albert Einstein explained its mechanism in the twentieth century.

For a hit-or-miss science, however, chemistry had many

The theory of evolution

Charles Darwin may be safely called the greatest biologist of the nineteenth century, but his ideas about evolution were neither entirely new nor complete. Indeed, it is one of the famous stories of science that Darwin's theory of evolution was made public in 1858 only because Alfred Wallace had reached the same conclusions as Darwin and mailed these to Darwin himself. Ever generous, Darwin arranged to present his work and Wallace's in the same session, so that neither would have priority, although Darwin had formulated the basic ideas many years earlier. It is unlikely, however, that evolution would have had the immediate impact that it did if the theory had been put forth by Wallace alone. Darwin was already well known for his account of the voyage of the *Beagle* and for his scientific work on that voyage. Furthermore, Darwin's *On the origin of species by means of natural selection or the preservation of favoured races in the struggle for life*—better known simply as *The origin of species*—published November 24, 1859, is one long, persuasive argument for the theory, which convinced many biologists of its truth through many examples.

But before there was *The origin of species* or Wallace's conclusions, biology had to progress to a point where the existence of evolution seemed reasonable and therefore deserved a scientific explanation. For one thing, there was no point to explaining the origin of species until a species was defined. The modern concept of species began with John Ray's 1686 definition, based on common descent. It was put into the form we still teach today by Comte de Buffon in 1749: a species is a group of interbreeding individuals who cannot breed successfully outside the group.

This concept of species assumed that species are immutable. Even though dogs or cabbages could be bred to many different shapes, for example, neither could be bred to the point that members of the species could not interbreed. In other words, one cannot develop a breed of dog that is of the cat species. Ancient writers who had a less clear concept of species believed that wheat seed could sometimes sprout as millet.

Most scientists of the seventeenth and eighteenth centuries also believed in a doctrine called *preformation.* This existed in two much argued versions, namely that the adult was preformed in the egg and that the adult was preformed in the sperm. In either case, preformation would seem to preclude one species giving birth to a member of another species. As the science of embryology became more precise, however, the doctrine of preformation—a potential barrier to a theory of evolution—was replaced by the doctrine of *epigenesis,* the development of the embryo from undifferentiated tissues.

A second factor in creating the climate for evolution was the emerging understanding of fossils as the remains of living creatures and the realization that many fossils were of species that no longer existed .

Late in the eighteenth century, a third precondition emerged—an understanding that the time required for evolution to occur was present in Earth's history. Both Abraham Gottlob Werner and James Hutton proposed processes for the development of geological features that required great stretches of time for Earth to have existed. Large amounts of time meant that evolution could take place so slowly that it would not be observed among living creatures. This was a necessary precondition, since evolution at the species level is not observable during a lifetime.

With that background, many scientists and near scientists of the first half of the nineteenth century believed in some form of evolution. Lamarck, one of the first evolutionists, thought, correctly, that the environment causes species to evolve. But he also thought that acquired characteristics of the parent could be inherited by the offspring; this was greeted with much disbelief in Lamarck's day and is still discounted today. Charles Darwin's own grandfather, Erasmus Darwin (one of the near scientists), offered a general theory of evolution by generation; it included not only living organisms but also Earth itself.

In England the most influential evolutionist before Charles Darwin was Robert Chambers. His 1844 *Vestiges of creation* influenced both Darwin and Wallace. Indeed, Wallace recognized that Chambers had the fact of evolution but did not have an explanation for it, setting Wallace on his own search for an explanation. Chambers was not a careful scientist, however, and his many errors put off many professional scientists.

After publication of *Origin of species* many—although not all—scientists were converted both to evolution and to the Darwin-Wallace theory of natural selection. The public was less convinced at first, especially those who took Darwinism to be atheistic (which Darwin did not consider it or himself to be). Many people also rejected Darwin's explicitly stated idea that humans and great apes share an ancestor. Two notable opponents of natural selection were Samuel Butler, the author of *The way of all flesh,* and George Bernard Shaw. Butler wanted to return to the ideas of Erasmus Darwin, and Shaw believed in a mystical life force. In the end, however, the theory of evolution and natural selection won all except those who continued to think that it contradicts the biblical account of Creation.

The theory of evolution did not arise fully formed in 1859, however. Modern evolutionists continue to improve on Darwin and Wallace, and a few have even rejected their ideas. New ideas have emerged, such as the concept of mutation and the laws of heredity. These new ideas combined with natural selection to form the basis for neo-Darwinism, the prevalent theory of evolution during most of the twentieth century. Since the 1940s, a theory of evolution has arisen that calls for rapid bursts of evolutionary change between long periods of species stability. This theory, often called "punctuated evolution," has most recently been articulated by Stephen Jay Gould and Niles Eldredge. The discovery of how heredity works has more exactly explained the mechanisms of the theory of evolution as well.

Chemists often heat substances to see what will happen. Some solids melt; other solids and some liquids vaporize. If the liquid or vapor is trapped and the heat lowered, the same material comes back. But some substances burn, char, or coagulate. After that happens, cooling will not bring back the original substance. For the most part, this second class of materials can be recognized as products of living creatures, while the class that only melts includes metals and other items produced from the earth. In 1807, Jöns Jakob Berzelius named the first class—those that melt—*inorganic* and the second—those that burn—*organic*.

Although it was known that new chemicals could be produced from organic sources—Pierre-Eugène-Marcelin Berthelot made the first of these *synthetics* as early as 1778—it was widely believed at the beginning of the nineteenth century that organic chemicals could not be synthesized from inorganic ones. Consequently, Friedrich Wöhler was astonished when in 1828 he heated some ammonium cyanate, classed as inorganic, and got urea, an organic chemical. We now know that ammonium cyanate is not, strictly speaking, inorganic, but Wöhler generally gets the credit for the first synthesis from inorganic material. People were astounded in his time. The popular idea that some mysterious *vital* principle was in organic chemicals had been dealt a severe blow.

Even if the vitalists were wrong, it was clear that organic chemicals were very different in some ways from inorganic chemicals. For one thing, chemicals that seemed to be exactly the same behaved differently. Jean-Baptiste Biot observed in 1815 that tartaric acid produced by grapes polarized light, while seemingly the same acid produced in the laboratory did not polarize light—but both acids had the same chemicals in the same proportions, or the same chemical formula. Justus von Liebig and Wöhler found other similar situations in the 1820s. When they analyzed various different organic compounds, they found that apparently different substances had exactly the same chemical formulas. In 1830, Berzelius named such pairs of compounds *isomers*.

Louis Pasteur's first major project as a young chemist was to try to unravel the mystery of why the two varieties of tartaric acid behaved differently. He observed a tiny difference among the crystals of the type of tartaric acid that did not affect light. After painstakingly separating the crystals into two groups, he discovered that one group polarized light just the way tartaric acid from grapes did. The other group also polarized light, but in the opposite direction. Pasteur correctly realized in 1844 that the two types of polarization cancelled each other out in the laboratory-made substance. He also understood that two different organic chemicals might have different properties and the same formula because the shape of the molecule might be different between the isomers.

In 1845 Adolph Wilhelm Hermann Kolbe became the first chemist to synthesize an organic compound (acetic acid) directly from chemical elements. Shortly after, the concepts of valence and bonding were introduced into chemistry. Friedrich August Kekulé began to use diagrams based on bonding in organic chemistry in 1861. Kekulé's diagrams showed that Pasteur was correct. The shape of an organic molecule determines its properties.

Even before a basic understanding of organic molecules developed, chemists were beginning to synthesize new organic compounds with important properties not available in inorganics. The first such synthetic, nitrocellulose, was found by accident by Christian Schönbein in 1846. Also known as guncotton, it was very explosive. Nitrocellulose was discovered when Schönbein's wife's apron, which he had used to wipe up a spilled mixture of acids, exploded and vanished in a puff of smoke. When others tried to manufacture guncotton in quantity, many were killed by premature explosions. Another synthetic discovered the same year, nitroglycerine, was only marginally safer. Eventually, however, both substances were tamed into cordite and dynamite. The modern age of high explosives was at hand.

Ten years later a young Englishman accidentally started another industry. William Perkin was trying to synthesize quinine when he produced the first synthetic dye, which we know as mauve. Perkin got rich on mauve and then went on to synthesize other chemicals. In 1875 he started his second industry by creating the first synthetic perfume ingredient, coumarin.

Although Perkin was English, he was something of an anomaly, for most of the organic chemists of the second half of the nineteenth century were German. In fact, Perkin's chemistry teacher, August Wilhelm von Hofmann, was a German chemist teaching in England. Hofmann synthesized his first dye, magenta, in 1858. After he returned to Germany, Hofmann continued to work on dyes and developed a number of violets. Other chemists in Germany worked on producing natural dyes from easily available chemicals, obtaining a red called alzarin in 1869 and indigo in 1880. All of these dyes became the basis of an immense German chemical industry. They also had an impact on biology, for biologists discovered that coloring bacteria or cells with dyes made previously invisible structures apparent.

Another group of organic chemicals got their start in England and the United States. In 1865 English chemist Alexander Parkes found a way to convert nitrocellulose to a nonexplosive (but still quite flammable) substance that we know as celluloid, the first plastic. This was improved on by American inventor John Wesley Hyatt, who was looking for a replacement for ivory billiard balls. In the twentieth century, English and American chemists continued to dominate the plastics industry, creating rayon, Bakelite, nylon, Teflon, Lucite, and polyester, among other synthetics.

In the late nineteenth century and the early twentieth, the raw materials for most of these synthetics were coal, water, and air. Later in the twentieth century, petroleum replaced coal, for there are generally fewer steps in a chemical process that starts with petroleum.

more hits than misses. The atomic theory, first proposed at the beginning of the nineteenth century, gradually became accepted over the course of the century, although there were a few skeptics even into the 1900s. As early as 1824, chemists discovered isomers—compounds with the same chemical formulas but different molecular structures. By 1848 Pasteur had worked out the mechanism by which two otherwise identical isomers behave differently in living organisms. Organic chemistry became a part of the broader field of chemistry in 1848 when Wöhler synthesized the first organic compound from inorganic components. Within organic chemistry itself, the first work with dyes gradually led to an enormous chemical industry. Chemists also began to understand the structure of organic molecules.

Earth science. Geology moved from its tentative beginnings at the end of the eighteenth century to become a major science in the nineteenth century. In particular, Charles Lyell convinced many of the truth of James Hutton's view of the ancient history of Earth. In turn, Lyell influenced Darwin in the development of the theory of evolution. One of the major developments that started with Lyell's work was the acceptance of a standard geologic time scale based largely on the presence of characteristic fossils in rock strata.

Major excitement came from discoveries of fossils, which were just beginning to be understood as the remains of species that no longer existed on Earth. The dinosaurs, first found and interpreted during this period, were especially exciting and prompted the rivalries of the bone-hunters of the American West. As an explanation of the extinctions that clearly had taken place, Georges Cuvier proposed that catastrophes had destroyed these early species. Darwin's view that small changes had removed some species superseded Cuvier's by the end of the period.

This is not to say that the catastrophe theory was rejected completely. Louis Agassiz promoted the idea that Earth had suffered an Ice Age, a concept that was gradually accepted as the century wore on and new evidence accumulated.

In fact, the nineteenth century had its own small catastrophe—the eruption and explosion of Krakatoa in what is now Indonesia, the major volcanic event of the period. It raised waves and colored sunsets around the world and was widely heralded as the loudest noise ever on Earth.

Fossils had another important use during the period. Geologists beginning with William Smith realized that different assemblages of fossils could be used to date rock strata that were many kilometers apart. If the same groups of fossils were present, the rocks had to be about the same age. This tool was used to work out the geologic history of Earth and to identify such ages as the Devonian and Cambrian.

The seismometer, which records the various types of waves produced by an earthquake, was developed duri the period. It would contribute to a much great understanding of the interior of Earth in the twentie century.

Mathematics. The reform movement in analysis was an a tempt to put the calculus of Newton and Leibniz and th followers on a logical basis. It was clear that the calcul (and the larger field of analysis, which includes calculu worked, but it was not clear why. In the 1820s Augusti Louis Cauchy redefined the calculus without using i finitesimals or appeals to intuition. Later in the centur Karl Weierstrass, Richard Dedekind, Georg Cantor, ar others worked to make analysis completely dependent c the arithmetic of natural numbers and their ratios, retur ing in a sense to the goals of the Pythagoreans (*se* "Mathematics and mysticism," p 36). This effort is co sidered to have been successful by most mathematician

Notable achievements at the beginning of the perio were the proof that quintics (polynomial equations of th fifth degree) cannot be solved by algebraic methods an the development of elliptic functions, both by Niels Abe who died at 26 of tuberculosis. Elliptic functions are func tions that have two periods, similar to trigonometric func tions that have one period.

Before the beginning of this period, Karl Friedrich Gaus had revived number theory and added considerably to it His work was the basis for number theory during the res of the nineteenth century. Gauss also developed new use for differential equations, which became a major topic o study during the century.

Early in the period, projective geometry emerged as a new variety of generalized geometry. It is concerned with the properties of figures that do not change when the figure is projected from one plane to another; it is, therefore, concerned with questions about the intersections of figures, but not with questions of measurement or parallelism, since measures are not preserved under projection.

Abstract systems, such as group theory (*see* "The legend of Galois," p 296), developed into whole branches of mathematics in their own right. At first mathematicians thought there might be some simple set of universal rules for numbers and numberlike entities. This view became untenable, however, when Sir William Rowan Hamilton realized in 1843 that there were numberlike entities of interest for which *a* times *b* does not necessarily equal *b* times *a*. Thereafter, algebra began increasingly to be concerned with sets of rules that describe specific structures such as rings and fields as well as groups. The study of such structures is termed abstract algebra.

A development related to abstract algebra and sometimes considered a part of it is Boolean algebra, a system developed by George Boole in 1854 for applying an algebraic system to the laws of thought. To some degree, however, Boolean algebra has been subsumed by two other major developments of the century, the rise of formal systems of symbolic logic and the creation of set theory.

Although Boolean algebra is a formal symbolic logic, it was not used when Gottlob Frege and Giuseppe Peano began their attempts to find a logical basis for arithmetic. They created new symbolic logics for this purpose. Symbolic logic in the sense of Frege and Peano was to become vital in the development of the foundations of mathematics in the twentieth century.

Set theory is almost purely the creation of Georg Cantor, although later mathematicians have axiomatized and expanded it. Set theory brought the actual infinite into mathematics for the first time. Since the time of the ancient Greeks, the infinite was viewed in terms of potential—a line could be extended as far as one liked, a larger number could always be found, and so forth. Cantor found ways to consider such sets as the complete set of natural numbers or the complete set of points on a plane, sets that are actually infinite. His work was not well accepted by his contemporaries, but it has been extraordinarily influential in the twentieth century. Basic operations with sets are similar to operations in Boolean algebra, although the symbolism is different.

Medicine. While the nineteenth century was a period of steady progress in understanding how the human body works, the most significant advances of the period were the discovery of anesthetics and the articulation of the germ theory of disease with the related development of vaccines for diseases other than smallpox.

Doctors had known from ancient times that alcohol ingestion could have a pain-deadening effect, but alcohol is not suitable as a way to kill pain during surgical procedures. It is too slow, for one thing. For another, the amount needed to produce unconsciousness is close to the amount that can cause death. In the 1840s, doctors and dentists found three substances that worked much better than alcohol: ether, nitrous oxide, and chloroform. Any of these anesthetics produces complete unconsciousness with no arousal by pain. Although all are dangerous, few patients were lost to the new anesthetics. With immobilized patients who felt no pain during the procedure, surgery could proceed toward developing the efficiency and delicacy that make it one of the most important branches of medicine today.

Previously, scientists believed that disease was caused by imbalances (the humoral theory of disease), bad air (the miasmal theory), or other conditions. The germ theory of disease replaced these ideas and formulated the concept that water supplies and air could transport disease, that doctors themselves could spread disease, and that certain small specific organisms could be found in conjunction with specific diseases. Louis Pasteur and Robert Koch not only were able to explain and extend these ideas, they were also able to develop methods of immunization against some diseases (*see* "The germ theory of disease," p 356). The theory became so entrenched by the end of the period that it was assumed even in cases where no disease-causing agent could be found, leading to the concept of filterable viruses.

Pasteur's success in producing immunity by vaccination is even more remarkable when one considers that the concept of an immune system was just being developed. In the 1880s Ilya Ilich Mechnikov discovered one aspect of the immune system. He found that white blood cells ingest and destroy foreign particles in the blood. Today we know that there are a host of different types of white blood cells, each with its own set of duties, forming the backbone of the immune system. Paul Ehrlich also studied white blood cells and later developed one of the first theories of antibodies near the end of the century.

Other important body systems just beginning to be understood in the nineteenth century were the two systems of hormones, the endocrine and the exocrine. In the 1820s and 1830s William Beaumont became the first person to study the digestive process in a living human when his patient Alexis St. Martin incurred a stomach wound that failed to close completely. Beaumont was able to perform a number of experiments on St. Martin that demonstrated that powerful chemicals in the stomach turn food into simpler substances. These chemicals are hormones of the exocrine system. Much later, in 1889, came the beginnings of knowledge of the endocrine system when it was observed that removal of a dog's pancreas produced symptoms of diabetes. Similarly, in 1894 it was found that ground-up adrenal glands produce physiological changes. Early in the twentieth century, these and similar observations were the bases of the development of the hormone theory.

Physics. As noted above, a major influence on both the science and technology of the nineteenth century was the discovery of the relationship between electricity and magnetism (*see* "Electricity and magnetism," p 270, and "From action at a distance to fields," p 334). Another thread that runs through the century is the science of heat, or thermodynamics. Thermodynamics was introduced as a concept as early as 1824 and its main laws worked out by 1865.

Often an important concept must be defined before progress can be made. Just as the concept of force was unclear before Newton's time, the concept of energy was unclear before the nineteenth century. Today children in elementary school are taught that a battery changes chemical energy to electrical energy or that friction changes the energy of motion (kinetic energy) to heat energy. These insights were made possible from 1842 through 1847 when Julius Mayer, James Prescott Joule, and Hermann von Helmholtz independently studied energy transformation and concluded that energy is not gained or lost as it is transformed from one type to another (the law of conservation of energy). By 1853 it was possible to relate these—

ideas to potential energy, such as the energy of position. The concept of energy was an essential prerequisite to Einstein's 1905 proof that energy and mass (matter) are two forms of the same thing.

The study of waves, especially light waves, also developed during the century, beginning with the discovery in 1842 of the Doppler effect: waves produced by a moving source are raised in frequency (higher in pitch for sound waves) when the source is moving toward an observer and lowered when the source is moving away. In 1848, Hippolyte Fizeau showed that the same effect occurs with light, implying that light from a source moving away from an observer will appear shifted to the red. Fizeau and Léon Foucault were able to measure the velocity of light using other methods, but in 1881 Albert Michelson developed the interferometer, which measures slight changes in a wave by comparing two versions of the same wave (*see* "Measuring with waves," p 520). Not only could this new device measure the speed of light with greater accuracy than previous measurements, it could also use a form of the Doppler effect to determine the absolute motion of Earth through space—assuming that there is a stationary substance called ether pervading space (*see* "Does the ether exist?," p 366). The negative conclusion of Michelson's measurement with Edward Morley in 1887 was not fully explained until Einstein's special relativity theory in 1905 (*see* "Relativity," p 384). In the meantime, James Clerk Maxwell's explanation of electromagnetism in terms of waves, discussed earlier, led to Heinrich Hertz's discovery of radio waves.

Toward the end of the century, many physicists began to experiment with the first vacuum tubes, based on the work of Heinrich Geissler, who developed the means of producing good vacuums starting in 1855. Using such a tube, the mathematician Julius Plücker discovered that rays could be produced in a vacuum tube. Named cathode rays by Eugen Goldstein in 1876, the rays were investigated extensively by William Crookes, who developed even better vacuums than Geissler had. Although Crookes came close to making fundamental discoveries with his Crookes tube, as it came to be known, others were to start the so-called second scientific revolution in 1895 based on discoveries made with the Crookes tube (*see* "Discovering new rays," p 388).

Technology. The impact of electromagnetism on the technology of communications and daily life was especially great. At the beginning of the nineteenth century, messages across a continent or across an ocean might take weeks to reach their recipients; well before the century was out, such messages were carried virtually instantaneously by telegraph, even across oceans. Even more revolutionary, the telephone connected people in a brand new way. After 1879 the electric light not only turned night into day, it also brought electric power into people's homes, where it would soon run small motors or heaters of all sorts.

Transportation was revolutionized as well. At the beginning of the century, the canal was still the best way to transport freight (the Erie Canal opened in 1824) and the steamboat was just beginning to replace sailing ships. But a year after the Erie Canal opened, the first practical locomotive service began. By 1869, railroads crossed North America and were ubiquitous in Europe. Ten years earlier, however, another element entered the transportation picture when Jean Lenoir developed the first internal-combustion engine. By 1885, Karl Benz was driving the first automobile, the destined major form of transportation of the twentieth century.

The third big technological change came from new construction materials and techniques, which included Portland cement, cheap steel, suspension bridges, and skyscrapers. The suspension bridge was pioneered as early as 1825, but it achieved dominance after the innovative techniques used to produce the Brooklyn Bridge, opened in 1883. As an alternative to a bridge, one could build a tunnel, with the first one under the Thames completed in 1843. Joseph Paxton's Crystal Palace in London in 1851 presaged techniques that would be used to build the first skyscrapers in Chicago, Illinois, starting in 1885.

A fourth change came from the advent of cheap steel with the Bessemer process. Closely connected to this was the use of steel in the new engines and machines that were developed and in the new construction techniques.

As noted in the discussion of chemistry above, the chemical industry arose during this century, especially in Germany.

New agricultural machines contributed to the ability of fewer farmers to feed and clothe a growing population.

Certain technological developments had a direct impact on other sciences. Various forms of photography, starting in 1822, were especially important to astronomy. Mechanical calculators, which became truly practical and available near the end of the century, would greatly simplify any scientific study that required computation—even though such pioneering calculators as the Burroughs adding machine and the Comptometer were intended for business use.

One attempted technology of the century did not get very far; however, it can be viewed from our vantage point as a singular effort. Charles Babbage designed a machine he called the Difference Engine in 1822 and even built a model of it. It was intended to calculate various functions automatically. But Babbage abandoned his Difference Engine in 1832 when he conceived the Analytical Engine, which we recognize today as a general-purpose mechanical computer. A working Analytical Engine was never achieved, but in 1890 an ingenious Herman Hollerith found a way to simplify handling the information from the US Census based on punched cards. Hollerith later founded the company that was to become IBM.

OVERVIEW

Science in the twentieth century through World War II

Beginning just before the start of the twentieth century, a series of related developments in physics—the discovery of X rays, radioactivity, subatomic particles, relativity, and quantum theory (*see* "Discovering new rays," p 388)—led to a profound revolution in how scientists view matter and energy. In turn, these developments affected to various degrees chemistry, astronomy, geology, biology, medicine, technology, and ultimately the fate of Earth, since they culminated with the first nuclear weapon, the atomic bomb, in 1945.

The growth of twentieth-century science

Science during the nineteenth century was still the occupation of only a few persons. During the twentieth century, however, the number of scientists became so large that it has almost become a cliché that more scientists have lived in the twentieth century than in all previous eras together. The nature of scientific research had profoundly changed as well; science became much more of a communal effort. Its progress was not only determined by the great discoveries of a talented few, such as Einstein, Bohr, and Rutherford, but also by the numerous small steps made by specialized researchers who did not have a famous formula or law named after them. Many scientific advances were also made by teams of researchers, each working on a small piece of the puzzle.

Many of the observations and discoveries made during the nineteenth century, such as the periodic table, Mendel's laws, and the negative result of Michelson's and Morley's experiment to measure the velocity of Earth against the ether (*See* "Does the ether exist?," p 366), were explained by new scientific theories that emerged in the twentieth century.

Not only the size of the scientific enterprise changed drastically, but also its influence on society at large. Science during the Renaissance and the Enlightenment had strongly influenced the philosophical outlook but had had little effect on society itself. During this century, scientific research became not only firmly entrenched in the universities but also in industry. After the example of the first industrial chemical laboratories in Germany from the nineteenth century, several industries founded their own research laboratories, seeing that not only applied research but also fundamental research was extremely important to technological progress. Among the most important of these was Bell Labs in the United States, founded by American Telephone and Telegraph.

Much of the methodology worked out by the great scientists during the nineteenth century started to bear fruit in the twentieth century. For example, the microscopic staining techniques developed during the late nineteenth century led to the discovery of many new organisms that cause disease. The synthesis of new chemical compounds became a daily occurrence.

During the nineteenth century society was transformed through technology; many of the great inventions, from the cotton gin to the electric light, were produced by people with little interest in or knowledge of basic science. But in the twentieth century, science itself started having an effect on society directly. For example, the timespan between a discovery and its technical application became much shorter. The discovery of the electron resulted in the construction of electron tubes in less than 20 years, with the ensuing revolution in communications, including broadcasting and long-distance telephoning.

Around 1900 Germany played the leading role in science and technology. Since the middle of the nineteenth century, Germany had been more successful in applying chemistry to industry; it became the leader in the production of dyestuffs and other chemical products. The development of the German pharmaceutical industry was a consequence of this industrial leadership. Germany lost its leading role in the sciences when Hitler came into power. Largely because of the influx of European scientists, the United States became the leading country of science. Between 1932 and 1938, eight of the 28 Nobel laureates in science were American, but these were native-born and not emigrés. After 1938, although the United States continued to be heavily represented among the Nobel laureates, many of the US winners had lived in Germany longer than they had lived in America. A country that failed to receive the influx of German emigrés, the Soviet Union, despite the native ability of its scientists, managed only two Nobel prizes in science from 1932 until today.

World War I had showed that science could play an important role in the outcome of a war. In Germany, more than 100 laboratories were involved in scientific research for the military. During the years after World War I, governments in the East and West started actively funding science, thus largely contributing to the enormous growth of science during the twentieth century. Except in Germany, where many scientists had fled the Nazi regime, scientists played a major role during World War II, their work culminating in the development of nuclear weapons.

New philosophies

Science in the first half of the twentieth century became highly successful in explaining the nature of matter, mechanisms of chemical reactions, fundamental processes of life, and the general structure of the universe. These successes of science started to exert a profound philosophical influence on the outlook of human beings, a phenomenon somewhat similar to the philosophical swing that occurred during the Enlightenment. The American philosophers C.S. Peirce and William James, founders of the philosophical school of pragmatism, held similar ideas to those of Ernst Mach: they believed that reality could be understood by experience alone. At the same time it became clear that science, especially mathematics, was also based on logical reasoning. The philosophical school termed "New Realism" combined the strictly empiricist views of James and Mach with Hegel's idea that knowledge can be attained only from *a priori* concepts by logic (although Mach believed that science is not only based on empirical facts, but also on underlying principles). The scientific view became the only acceptable view of reality and in many cases the model for philosophical thinking.

Darwin's theory of evolution also had a major impact on philosophers, especially Herbert Spencer, Henri Bergson, and John Dewey. Natural selection, which is the basis of Darwin's theory of evolution (*see* "The theory of evolution," p 275), became a principle accepted in the social sciences and psychology. Spencer's ideas had become almost a philosophical system: evolution and natural selection were not only the fundamental laws of the living world, but also of society, an idea that resulted in the laissez-faire political philosophies of the first decades of the twentieth century.

Changes in mathematics and the development of psychology also had important philosophical implications.

Quantum reality

Another prominent scientific concept that changed the way philosophers think about the universe is quantum theory. Around the end of the nineteenth century, Newton's mechanics proved to fail in several areas. It became clear that one cannot trace all physical phenomena back to classical mechanics. To solve these problems physicists developed quantum mechanics and abandoned several of the tenets of classical physics. Wolfgang Pauli and Werner Heisenberg introduced theories in which the visualization of phenomena (as was possible in classical physics) was eliminated. Erwin Schrödinger developed an equivalent theory that was later interpreted in terms of waves of probability. In this theory, the electron could not be viewed as a point mass orbiting the nucleus, but as a wave train showing where the electron might be. The idea that each particle could be associated with a wave came from Louis de Broglie, and experiments had shown that electrons could behave as waves when they pass through crystals and are diffracted.

In 1927 Heisenberg introduced one of the most fundamental principles of quantum mechanics: It is not possible to simultaneously observe the position and the speed of a particle (such as the electron) with absolute accuracy. This principle is known as the principle of uncertainty, and Bohr incorporated it into his concept of complementarity: If you observe a system, you interact with it, disturbing it. Bohr elevated the concept of complementarity to a fundamental principle of the natural sciences; it includes the complementarity between the wave and the particle theory of light. Light can be viewed as a wave, for example, when it is diffracted passing through a narrow slit, or as a particle, when ejecting an electron from a metal surface in the photoelectric effect.

These changes affected the way scientists viewed reality in fundamental ways.

Major advances

Anthropology and archaeology. In 1895 Eugène Dubois brought to Europe his Javanese fossils of what we now call *Homo erectus* (the "Java ape-man"), the first hominid that most anthropologists considered a different species from *H. sapiens.* Dubois' discovery met considerable resistance and he eventually took his specimens and hid them under floorboards of his house. In the early twentieth century, however, more fossils of *H. erectus* were found in China and Africa, confirming the new species. Sadly, one of the greatest collections of *H. erectus* fossils, the "Peking man" specimens, were lost during World War II and have never been found.

The other great discovery in physical anthropology during the period started when Raymond Dart was given the fossilized head of a child to examine. He correctly recognized that the "Taung child" represented a new genus, closely related to *Homo,* which he named *Australopithecus.* As with the Dubois discovery, Dart's ideas were rejected at first, but a search for other fossils of australopithecines, as the members of the new genus are called, produced many new fossils and was eventually convincing. Interpretation of the meaning of the new species is still going on.

Our view of our more recent ancestors was changed considerably by the discovery of a young girl in 1879, when the Altamira cave paintings were found. However, this discovery was rejected as a fake until the beginning of our period. Discovery of the La Mouthe cave paintings by four boys in 1895 reduced the cries of forgery to whispers. With other examples found in 1896 and 1901, the reality of paleolithic art was beyond question. When four other young boys found the Lascaux cave paintings in 1940, the greatness of some of the paleolithic artists was also realized.

This period also includes virtually all of the development of cultural anthropology. Although the earlier nineteenth century included some studies of American Indians, the history of cultural anthropology is usually taken to begin in 1896 with Franz Boas's department of anthropology at Columbia University, the first such department anywhere. Another major factor was the expeditions of the American Museum of Natural History (in New York), starting in 1900, to study the peoples of eastern Siberia to see whether they are the ancestors of American Indians. The major

The quantum

One of the most important tools of science had its start in 1665 or 1666 when young Isaac Newton observed that a prism demonstrates that white light is a mixture of the colors of the rainbow. Although scientists realized earlier that the rainbow is formed when light is broken into different colors (the spectrum), Newton was the first to make a thorough study of the subject. Later, other scientists investigated this effect for light produced by heating different elements: from this investigation we learned of the composition of the stars. It is well known that study of the spectrum reveals the composition of a heated body or gas. Much less well known is that this study also reveals much about the atom.

The spectrum not only appears in the rainbow, it is hidden in another effect. An observation that must have been made in antiquity is that as iron is heated to forge it, it first becomes dull red, then brighter red, and gradually white. Other solid materials that do not burn behave much the same way. After formulation of the electromagnetic theory of light, theorists tried to explain this phenomenon from first principles. It was apparent that longer wavelengths appear at moderate temperatures. As the temperature rises, shorter and shorter wavelengths begin to appear. When the material becomes white hot, all the wavelengths are represented. Studies of even hotter bodies—stars—showed that in the next stage the longer wavelengths drop out, so that the color gradually moves toward the blue part of the spectrum.

Efforts to make theoretical sense of the way the spectrum gradually appears and disappears were at first unsuccessful. For one thing, theory suggested that a perfectly black body—one that absorbs every wavelength of electromagnetic radiation equally well—would, upon heating, radiate every wavelength equally well. Experiments with simulated black bodies, however, showed that they behave in the same way that iron does when it is heated. In the 1890s Wilhelm Wien and Lord Rayleigh each tried to find a formula to explain these phenomena, but each failed in a different way. Wien's formula worked near the blue end of the spectrum and above, but failed for long wavelengths. Rayleigh's formula was just the opposite, good for long wavelengths and not for short.

In 1900 Max Planck found an explanation that worked for all wavelengths, but little attention was paid to it. Planck made the assumption—which seemed quite odd at the time, even to Planck—that electromagnetic radiation could only be emitted in packets of a definite size, which he called quanta. People took notice of Planck's quantum only when Albert Einstein, in 1905, used the idea to explain the photoelectric effect, to reconcile theory and experiment for heat, and to account for the propagation of light without relying on an "ether." It appeared that Planck's quanta went beyond theory and had a physical reality.

By 1911 Ernest Rutherford had established that the atom has a positive nucleus surrounded by orbiting electrons. Like

The quantum (continued)

the black-body problem, however, the theory of the atom did not match experiment. Electrons orbiting a nucleus should give off radiation constantly, resulting in the electron falling into the nucleus. But atoms do not give off that kind of energy and they are usually quite stable.

Niels Bohr turned to Planck's quantum to salvage the theory. The size of the quantum, based on a pure number called Planck's constant, could be calculated. Starting in 1913, Bohr calculated the quantum of the simplest case, hydrogen, in which a single electron orbits a proton. He showed that experiment and theory could be reconciled by saying that the quantum restricts the electron to particular orbits. For each counting number (1, 2, 3, . . .) there was one permissible orbit. For a given electron, the orbit it was in could be assigned that number, called its quantum number. Bohr based his calculations on the lines that form the spectrum of hydrogen gas (when a pure gas is heated, the spectrum consists of discontinuous lines, not a full rainbow). Bohr explained the lines by saying the light is emitted when the electron changes from a higher quantum number to a lower one. There was not a continuous spectrum because the electron moved from orbit to orbit in "quantum jumps." More complex atoms were beyond direct calculations, but approximations indicated that the same approach was correct.

But there were minor complications. Bohr's model explained the large lines in the spectrum, but these lines are broken into smaller lines, called the fine structure of the spectrum. In 1915, Arnold Sommerfeld introduced a second quantum number to explain the fine structure. This was based on the idea that orbits allowed to electrons are ellipses, not circles. Next, it was observed that since the spectrum is affected by a magnet—the Zeeman effect—so there needs to be a third quantum number to account for the magnetic state of the electron. Finally, in 1925 George Uhlenbeck and Samuel Goudsmit found that electrons spin, necessitating yet another quantum number. Each number is an integer that describes the specific state of the electron. If you know that the numbers are, say, 3, 1, 1, 2, then you have a precise description of the electron it its orbit.

The discovery of spin was a major breakthrough, resulting in the rapid development of what is now known as the quantum theory. In 1925 Wolfgang Pauli determined that four quantum numbers is just right. Everything known about an electron in an atom can be reduced to the four numbers. Furthermore, no two electrons in an atom can have the same numbers. This Pauli exclusion principle, as it became known, accounts for how electrons are arranged in all atoms and tells why sulfur has different properties than tin.

About the same time, Werner Heisenberg found that arrays of quantum numbers could be used to calculate lines in the spectrum. This is called the Heisenberg matrix mechanics.

Earlier, Louis de Broglie had proposed that every particle has a wave associated with it. Erwin Schrödinger used de Broglie's idea to calculate the spectral lines. Later it was shown that the Heisenberg matrix mechanics and the Schrödinger wave equation were equivalent.

In 1927 Heisenberg put forward the idea that it was theoretically impossible to determine the position and the momentum of an electron at the same time. The greater the degree of accuracy about one quantity, the less the accuracy of the other. This uncertainty principle, as it is known, was later extended to other particles and other quantities. Max Born suggested that the Schrödinger equation could be interpreted as giving the probability that an electron is located in a particular orbit. This interpretation is still the most common in quantum theory.

Although Schrödinger's wave equation gives good results, they are not perfect. The wave equation does not take spin or the theory of relativity into effect. In 1928, Paul Adrien Maurice Dirac revised the equation to include spin and relativity. Dirac's theory was important because it revealed for the first time the existence of antimatter, but the mathematics is so complicated that physicists still use the Schrödinger wave equation. Dirac's theory essentially completed classical quantum theory.

After World War II, physicists developed quantum electrodynamics, a method of calculating the behavior of electrons and other particles that is even more precise than classical quantum theory.

works of Bronislaw Malinowski during World War I and immediately after, Margaret Mead during the 1920s, and Ruth Benedict in the 1930s seemed to define cultural anthropology.

Certainly the most astonishing achievement of archaeology during this period was the discovery of the Minoan civilization on Crete by Arthur Evans beginning in 1900. Like Schliemann before him, Evans was guided in part by legend and literature. The palaces and plumbing of Knossos, the principal city of the Minoan civilization, dazzled the world, although inability to read the inscriptions frustrated everyone. (This was partially resolved in 1953 when Michael Ventris deciphered one of the two forms of Minoan script.)

Almost as astonishing was the discovery in 1911 of Machu Picchu in the Peruvian Andes by Hiram Bingham. Bingham was looking for the retreat to which the last Inca (the ruler of the people also called Inca) had fled during the Spanish conquest, a retreat never seen by Europeans. On top of a high mountain, he found a vast city that dated from the *first* Inca, about 1000 AD. Later, he realized that it was the retreat of the last Inca as well.

Finally, we cannot leave out the most famous discovery of all, Howard Carter's finding of the tomb of Tutankhamen in 1922. Because of the treasure and legends associated with the find, "King Tut" came to represent the type of discovery that was the goal of archaeologists in the early twentieth century.

At the same time, however, archaeology was turning away from searches for spectacular finds and turning toward a more scientific study of the past, a trend that would accelerate after World War II.

Astronomy. At the beginning of this century astronomers held that the sun was one of the many stars comprising a huge system called the Milky Way that filled the entire universe.

Many of the fuzzy objects that had been observed for over 200 years, such as the Andromeda nebula, were believed to be objects within the Milky Way galaxy. An important breakthrough—the discovery that one could determine the distance of a certain type of variable star, the Cepheids, by observing their variation period—allowed astronomers to measure the distance of some of the closer "nebulas". By observing Cepheid variables in the Andromeda nebula, Edwin Powell Hubble discovered that it was at an enormous distance from our galaxy, and that in fact it was a galactic system comparable in size and shape to our own.

From the spectra of galaxies Hubble could derive their velocity relative to us. From this, he made a second surprising discovery. During the 1920s he found that the greater the distance of a galaxy, the faster it is moving away from us (*see* "The size of the universe," p 440). This discovery formed the observational basis of the model of the expanding universe and the Big Bang.

In solar system astronomy, the most notable achievement was the expansion of the solar system to nine planets, with the discovery of Pluto in 1930. Today, however, Pluto still seems to be an unlikely addition to the system, and it is not clear what its significance is.

A major achievement of astronomy during the period was the development of understanding of the life cycle of a typical star. As stars were classified into gas giants, white dwarfs, and so forth it became apparent that stars of different ages tended to fall into certain categories. The Hertzsprung-Russell diagram showed these relationships graphically.

Biology. The foundations of experimental biology were laid during the nineteenth century. Fundamental research in heredity started with the rediscovery of Mendel's work by de Vries, Correns, and Tschermak in 1900. The concept of a "gene," a unit of inherited characteristics, such as the color of a flower, or in humans the color of the eyes, made it possible to understand how these characteristics were transmitted through generations. The role of genes in the production of enzymes in the cells of organisms also became understood and led to the "one gene—one enzyme" theory. What the compound was that contained the genetic information became clear only during the early 1940s, when biologists discovered that DNA is the substance that transmits genetic information (*see* "Discovering DNA," p 492).

The role of mutations, sudden changes in the transfer of inherited characteristics, became clear in the mechanism of evolution. The fruit fly, in which the four chromosomes are clearly visible, and mutants are clearly distinguishable (for example, by the shape of wings), became the most important subject for the study of mutations.

Biology gained enormously from the advances made in chemistry, especially from the study of organic compounds. The application of chemistry to biology gave rise to a new important discipline, biochemistry.

The role of certain substances, such as enzymes and hormones produced by living organisms, became understood, and the importance of hormones to many disorders, such as diabetes, was recognized.

Chemistry. With the understanding of the structure of the atom, chemists could explain many of the chemical properties of elements and compounds.

Scientists recognized that the periodicity of the chemical characteristics in Mendeléev's table reflected a periodicity in the configuration of the electrons in the outer layer of an atom. It is possible to explain the chemical properties of elements uniquely by the configuration of these outer electrons of the atom. The development of the theory of chemical bonding by Linus Pauling in the 1930s explained the role of electrons in the formation of molecules: atoms could be bound together either by electrostatic forces (ionic bonding) or by sharing electrons (covalent bonding). The newly developed quantum mechanics formed the theoretical underpinnings of the study of the chemical bonding and the interpretation of atomic and molecular spectra, making spectroscopy a powerful analytical tool. Spectroscopy was used not only in visible light but also in infrared and microwave regions of the spectrum.

Reaction mechanisms and velocities also were the objects of a large number of studies. The study of polymerization reactions led to the development of many compounds made up of macromolecules, such as artificial fibers and the first plastic materials. The chemistry of silicone, which can form complex compounds similarly to carbon, led to the development of the synthesis of silicones, which became important industrial compounds after World War II.

Earth science. From our perspective today, it is easy to see Alfred Wegener's theory of continental drift as the main event in earth science in the first part of the twentieth century; but geologists during this period generally rejected Wegener's ideas. They were not to be generally accepted (in a somewhat modified form) until the 1960s.

Most of the progress in geology that was recognized at the time came from the use of earthquake waves to determine the internal structure of Earth. It was during this period that geologists discovered that Earth has a crust, a mantle, an outer core, and an inner core. The knowledge of radioactivity quickly led to the idea that the age of a rock could be determined from the ratio of a radioactive element to its stable decay product (*see* "The age of the Earth," p 404). This period also marks the beginnings of the systematic study of volcanoes.

Oceanography benefited from the German *Meteor* expedition, which used sonar to discover the mid-Atlantic ridge. William Beebe also began the first efforts to explore the deeper parts of the ocean. Oceanography would not fully become a science, however, until after World War II.

Another part of earth science that saw progress was meteorology. The role of air masses was identified and groundwork was laid for numerical methods of weather prediction.

Mathematics. During the end of the nineteenth century, mathematicians had engaged in a massive effort to develop a purely logical basis to mathematics. One of the first attempts to find an axiomatic basis for mathematics was undertaken by David Hilbert. He proposed that a system of mathematical foundations should satisfy three requirements: it should be consistent, complete, and decidable. The existence of infinite sets, however, led to paradoxes. In 1931 Kurt Gödel proved that Hilbert's ideas could not be realized: mathematics could not be both consistent and complete (*see* "The limits of mathematics," p 462).

Alfred North Whitehead, Bertrand Russell, and Giuseppe Peano extended algebra from symbols for numbers to symbols for concepts, creating symbolic logic. In France during the 1930s, a group of mathematicians working under the pseudonym of N. Bourbaki started the task of giving mathematics an axiomatic basis by searching for those structures that form the basis of the different mathematical theories (*see* "The mathematics of N. Bourbaki," p 471). Another group, led by Emmy Noether at Göttingen in Germany, developed abstract algebras that could represent any type of system.

The concept of an integral had been generalized by T.J. Stieltjes in the nineteenth century, but the definitive expansion of the definition came in 1902 in connection with the measure theory of Henri Lebesgue. In turn, Lebesgue's work combined with set theory and topology, also nineteenth-century ideas, merged into the new discipline of functional analysis, the mainstream of analysis in the twentieth century.

Other developments were so numerous that they can only be mentioned here: the axiomatization and extension of probability, algebraic geometry, optimization theory, analytic number theory, the theory of integral equations, and stochastic processes, among others. Mathematics in the twentieth century reached the point that science had in the nineteenth. No longer could any one mathematician be competent in all branches of the subject.

Medicine. The identification of organisms causing disease started in the nineteenth century by a number of scientists such as Koch and Pasteur, continued throughout the twentieth century. Also, several of the toxins secreted by microorganisms, often the compounds causing the disease, became identified. Several antimicrobial agents, such as those based on sulfamides, were developed; the most important of these was penicillin, a fungus with antibiotic properties discovered by accident by Alexander Fleming. The introduction of penicillin and other antibiotics made many formerly fatal diseases, such as tuberculosis, curable.

By the 1930s several infectious diseases were known whose agent, called a virus, was so small that it remained invisible in the ordinary microscope. The first virus to become isolated was the tobacco mosaic virus, which could be crystallized, and of which it is now known that the main constituents are nucleic acid and proteins. With the introduction of the electron microscope during the 1940s, it became possible to photograph viruses directly.

The role of hormones and certain important agents in food, called vitamins, became clear in health care. During the first decade it was discovered that the absence of thiamine is the cause of beriberi and the absence of insulin production is the cause of one type of diabetes. Diabetes became treatable by the administration of insulin extracted from animals.

Psychology made further progress and was often based on experiments with animals. The importance of childhood experiences and sex in the development of affective disorders was emphasized in the work of Sigmund Freud, who influenced society at large, as well as science. Several schools of thought developed, each with different forms of treatments for psychic disorders.

Physics. Physics underwent a revolution during the first decades of this century. Ideas about space and time, continuity, and cause and effect, which were the underpinnings of Newtonian mechanics, changed fundamentally because of two important developments: the introduction of relativity theory by Einstein and the advent of quantum mechanics. The first development, however, was the understanding of the structure of the atom, brought about by a series of important discoveries.

Until the end of the nineteenth century, physicists assumed that all phenomena encountered in physics could be explained by the motion of particles following Newton's laws of motion. One notable example was that the classical theory could not explain the repartition of energy in the molecules of a gas and the energy distribution of radiation emitted by hot bodies. These problems led Max Planck to announce in 1900 a revolutionary postulate in physics: energy can only be given off by matter in small packets, called quanta (*see* "The quantum," p 380). What exactly these quanta were became clearer in 1905 when Einstein introduced the concept of the photon: light travels in small

Until the end of the nineteenth century, physicists believed that all physical phenomena, ranging from the motion of atoms to that of celestial bodies, were governed by one set of laws: the laws of motion formulated by Newton in the *Principia*. Newton's theory implied that these laws were also valid for systems that move at constant speed relative to each other. That laws stay the same for such systems is known as the principle of relativity. Consequently, it is impossible to find out whether a system is uniformly moving or not by performing mechanical experiments. A fundamental concept of Newtonian physics is the existence of absolute space. During the nineteenth century, when Thomas Young showed that light is a wave phenomenon, an invisible substance called "ether," linked to absolute space, was believed to be the medium that carried these waves.

During the 1880s Albert A. Michelson and Edward Williams Morley attempted to measure the velocity of Earth relative to the ether by measuring the velocity of light. Their experiments showed that the velocity of light is exactly the same in every direction and thus does not depend on the proper motion of Earth. Some physicists argued that this result showed that the principle of relativity did not apply to electromagnetic radiation. The Dutch physicist Hendrik Antoon Lorentz and and the Irish physicist George FitzGerald tried to explain the result that the velocity of light seemed independent from the motion of Earth by assuming that everything contracts in the direction in which one is moving. They argued that the instrument that Michelson and Morley had used contracted imperceptibly in the direction of Earth's motion, thus falsifying the measurement of the velocity of light. Perhaps the most important aspect of their theory is that they held on to the idea of an ether.

In 1905 Albert Einstein published a theory based on the notion that it is impossible to determine the absolute motion of a moving object. Einstein's concern, however, was not the failure of Michelson and Morley to measure the motion of Earth relative to the ether, but the validity of James Clerk Maxwell's electromagnetic theory in systems that move at speeds close to the velocity of light. Einstein's theory did not require the presence of an ether and was based on the following assumptions: (1) absolute speed cannot be measured, only speed relative to some other object; (2) the measured value of the speed of light in a vacuum is always the same no matter how fast the observer or light source is moving; and (3) the maximum velocity that can be attained in the universe is that of light.

Einstein's theory was called the "special" theory of relativity because it applied the principle of relativity only to systems in uniform motion relative to each other.

Because of the principle of relativity, passengers who are traveling smoothly in a train cannot tell whether they are moving or not unless they look out of a window. The situation becomes different if the train is uniformly accelerated. The passengers will feel a slight push in the direction opposite to that in which the train is moving. This is termed *acceleration force:* because of this extra force it appears that the laws of physics would be different for bodies accelerated with respect to each other.

In 1916 Einstein published his general theory of relativity, which he based on the assumption that the laws of physics would also be the same in systems that are accelerated relative to each other. To formulate this theory, he introduced the principle of equivalence: acceleration forces and gravitational forces are not distinguishable from each other. Einstein argued that if one were in a closed elevator that is uniformly accelerated upward, one would perceive a force that is indistinguishable from gravitation. The principle of equivalence can also be expressed by saying that the inertia of an object (its reluctance to be set in motion) is proportional to its mass. The principle of equivalence was already known to Galileo, who had deduced it from his experiments with wooden balls rolling down sloping planes. In 1891 the Hungarian scientist Roland Eötvös made precise measurements and established that inertial and gravitational mass are equivalent to an extremely high degree. Because acceleration forces and gravitational forces are equivalent, they should not be distinguishable, but viewed as a property of space.

In a formulation of the special theory, the mathematician Hermann Minkowski had introduced a four-dimensional space in which the fourth dimension is time. In this space-time continuum as adapted to the general theory, gravitation corresponds to the amount of curvature in a non-Euclidean, four-dimensional space. Near a large mass, space becomes more curved, and objects moving near that mass will follow the curvature of space.

One of the interesting consequences of the equivalence of gravitation and acceleration force is the bending of light rays by the presence of large masses, such as a star or planet. For example, if light enters through a small hole on one side of an spaceship that is accelerated, the light ray will reach the other side after the spaceship has moved. The same effect would exist if the spaceship were to come close to a massive planet or star. To an observer in the spaceship, the light ray will appear curved in either case. But the observer cannot tell whether the spaceship is being accelerated or is near a planet or star.

In 1919, during a solar eclipse, Arthur Eddington showed that stars whose light passes close to the sun appear to be displaced by a minute amount that corresponds to the value calculated by Einstein. This was the first experimental proof of the general theory of relativity. Several other experiments more recently have had results that eliminate most doubts about either theory of relativity among physicists.

packets called photons; this was reminiscent of Newton's idea that light consists of vibrating particles. According to Einstein, light is only emitted in small packets, but it also can only be absorbed in small packets. Physicists had observed that certain metals eject electrons when placed in a strong light and that the speed of these ejected electrons does not depend on the intensity of light but on its color. This is called the photoelectric effect. Einstein explained the photoelectric effect by assuming that an electron is only ejected when directly hit by a photon, and that the energy of the photon does not depend on the intensity of the light but on its wavelength (color).

One of the major problems that physics solved at the end of the nineteenth century was the nature of cathode rays. The discovery that these rays consist of minute particles with negative electrical charge, called electrons, and the discoveries of X rays and radioactivity opened the way to the understanding of the structure of the atom during the first decades of the twentieth century (*see* "The electron and the atom," p 392). Rutherford succeeded in identifying the particles that were emitted by radioactive substances and the changes in the atoms that emitted these particles. By bombarding atoms with alpha particles, Rutherford found that some alpha particles were deflected from their path almost directly back along the same path. From this observation he concluded that an atom must consist of a very dense nucleus of positive charge around which revolve electrons like planets in a miniature planetary system.

The model of the atom described by Ernest Rutherford in 1911, a nucleus around which pointlike electrons orbited like planets, had an important flaw. The moving electrons should emit electromagnetic waves, gradually lose energy, and ultimately fall onto the nucleus. Niels Bohr solved this problem by introducing a model of the atom that incorporated a principle similar to Planck's hypothesis of quanta: electrons occupy fixed energy levels in the atom and can only absorb or emit energy by jumping from one energy level to another. Bohr's model of the atom also explained the spectrum of the hydrogen atom.

Bohr's theory, however, was still fraught with theoretical problems. For example, his theory could not explain the spectra of atoms more complex than hydrogen. Also, certain results of Maxwell's electrodynamic theory were inconsistent with other existing theories. In 1905 Albert Einstein published his theory of special relativity, a theory of mechanics consistent with electrodynamics. In 1915 Einstein published his general relativity theory, which solved problems with gravity that were not explained by the special theory (*see* "Relativity," p 384). Special relativity theory also explained the negative result of the Michelson-Morley experiment, while general relativity explained the minute rotation of Mercury's perihelion, which had been observed earlier. Einstein's general theory also predicted that light would be bent by massive objects. The bending of light by mass was experimentally confirmed by an expedition led by Arthur Eddington that measured the displacement of a star close to the limb of the sun during an eclipse in 1919.

The first artificial nuclear reactions were achieved shortly before the Second World War by Otto Hahn and Fritz Strassmann. This led to the development of the atomic bomb during World War II (*see* "Scientists and World War II," p 480).

Technology. In the twentieth century the extent of the dependence of technology on basic science became clear. The discovery of the electron gave rise to an entirely new technology, electronics. This was comparable to the development of the chemical industry in Germany during the nineteenth century based on discoveries in chemistry.

The technological device that transformed society most profoundly during this period was the electronic vacuum tube, an extremely versatile device that became the heart of the development of electronics during the first half of the twentieth century. The most important aspect of the vacuum tube was that it could amplify electric audio signals (for example, in telephone lines) and that it could generate, amplify, and detect high-frequency signals (radio waves). The first applications of vacuum tubes were in the amplification of telephone signals, making long-distance telephone connections possible. The vacuum tube was at the heart of the enormous development of radio broadcasting during the 1920s and 1930s and of television in the 1940s.

Transportation also underwent a revolution. Automobiles, fragile and impractical at the beginning of the century, became a widely popular and dependable mode of transportation. Both world wars accelerated technological development enormously. Airplanes, developed shortly before World War I, received a strong impetus during that war; the modern jet plane is the consequence of developments during World War II. Electronics also had a strong impetus during both wars: voice radio communication developed during World War I and radar during World War II.

Some of the first working electronic computers were also the result of military needs. The mathematician Norbert Wiener developed an electronic gun-pointing device based on the feedback mechanism, and Alan Turing developed an electronic computer that could break successfully the almost unbreakable "Enigma" code used by German forces. Others, however, had preceded them. The first electronic digital computer was developed in the late 1930s and early 1940s by John V. Atanasoff and Clifford E. Berry for the purpose of solving systems of equations. In the case of the Atanasoff-Berry Computer, or ABC, the war prevented complete development, as both inventors were drafted for other wartime duties. Nevertheless, ideas based on the ABC were used in creating ENIAC, the first general-purpose electronic digital computer, operational by 1945.

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I

The Science of Optics

Something very like the discipline that we know today as optics existed during the Middle Ages as the science of *perspectiva*. This science was concerned with such matters as the nature and propagation of light and color, the eye and vision, the properties of mirrors and refracting surfaces, image-formation by reflection and refraction, and meteorological phenomena involving light. Moreover, it took a broad view of these topics, refusing to confine itself to mathematical description or causal analysis, but insisting on a unified approach that investigated the mathematics, the physics, the physiology, and even (to a limited extent) the psychology and epistemology of the visual process.

Such an inclusive and broadly based discipline had not always existed, nor did it ever attract large numbers of adherents. It came into existence largely through the efforts of Ibn al-Haytham (known to the Latin world as Alhazen or Alhacen) and appeared in the West in the thirteenth century under the aegis of Roger Bacon; but even then the majority of scholars working in any area of what we now call optics continued to regard the mathematics, physics (sometimes accompanied by psychology or epistemology), and physiology of light and vision as distinct enterprises and preferred to practice one or another of them in isolation from the rest. In short, the old disciplinary boundary lines continued to exercise a strong influence on scholarship, and for most of the Middle Ages the perspectivists (the practitioners of *perspectiva*) struggled on behalf of a losing cause. In the end, however, Johannes Kepler took up the tradition of *perspectiva*, and through him it became the foundation for the modern science of optics.

Our first task, then, must be to consider the shape of the optical enterprise, its aims and criteria, and the various traditions that it comprised. As a vehicle for this investigation I propose to examine the development of medieval theories of vision. Not only will visual theory admirably illustrate changing conceptions of what optics was about, but in itself it was one of the central themes of medieval optics and, hence, deserving of close attention for its own sake. When we have completed this analysis of medieval visual theory, we will turn to the other major strand of medieval optics—theories of the nature and propagation of light and color.

Theories of Vision in Antiquity

Because medieval theories of vision developed out of ancient antecedents, we must begin with a brief examination of visual theory in antiquity.[1] The common premise of all ancient theories of vision was that there must be some form of contact between the object of vision and the visual organ, for only thus could an object stimulate or influence the visual power and be perceived. Now in general there appeared to be three ways in which contact could be established. The object could send its image or ray through the intervening space to the eye; the eye could send forth a ray or power to the object; or contact could be established through a medium (usually air) that intervened between the object and the eye.

The first of these alternatives was developed by the atomists, who argued that thin films of atoms depart from visible objects in all directions, maintaining a fixed configuration as they proceed, and enter the eye of an observer. Epicurus explained:

> For particles are continually streaming off from the surface of bodies, though no diminution of the bodies is observed, because other particles take their place. And those given off for a long time retain the position and arrangement which their atoms had when they formed part of the solid bodies. . . . We must also consider that it is by the entrance of something coming from external objects that we see their shapes and think of them. For external things would not stamp on us their own nature of colour and form through the medium of the air which is between them and us, or by means of rays of light or currents of any sort going from us to them, so well as by the entrance into our eyes or minds, to

> whichever their size is suitable, of certain films coming from the things themselves, these films or outlines being of the same colour and shape as the external things themselves.[2]

These thin films (*eidola* in Greek, *simulacra* in Latin) were compared by Lucretius to the skin of a snake or cicada.[3] They were regarded as coherent assemblies or convoys of atoms, capable of communicating to an observer all of the visible qualities of the objects from which they issued; to receive a series of such images was to gain a visual impression of the object itself.[4]

If the atomistic theory can be called an "intromission" theory of vision, because radiation is sent to the observer, then the obvious alternative is an "extramission" theory, in which radiation is sent out from the observer's eye to "feel" the visible object. This theory, which was proposed by Euclid and further developed by the mathematician and astronomer Ptolemy, maintained that radiation issues from the observer's eye in the form of a cone and proceeds in straight lines unless reflected or refracted. If it falls on an opaque object the object is perceived, and the perception is (in some unexplained manner) returned or communicated to the sense organ.[5]

But there were obvious difficulties in both the atomistic intromission theory and the Euclidean extramission theory. Against the former it could be objected that the *eidola* of a large object would be unable to shrink sufficiently to enter the observer's eye or that *eidola* would be unable to pass through one another (when the lines of sight of two observers cross) without interference. Against the latter, one could note the absurdity of supposing that a physical ray can issue from the eye to something as remote as the fixed stars (and this in an imperceptible instant). Objections such as these led Aristotle to propose, as a third alternative, that the visible object sends its visible qualities through the intervening air (or other transparent medium) to the observer's eye. Colored bodies produce qualitative changes in the transparent medium, and these changes are instantaneously propagated to the transparent humors of the observer's eye. Thus, a green object in some sense colors the observer's eye green, and this acquisition of color constitutes the act of seeing. The eye does not *receive* the visible object, as in the atomistic theory, but *becomes* the visible object.[6]

Aristotle's theory of vision might be called (in the absence of a better term) "mediumistic," for contact between object and observer is established through the medium. An alternative mediumistic theory was defended by the physician Galen, who argued that visual spirit descending from the brain through the optic nerve to the eye emerges from the eye for a short distance and transforms the surrounding air, which thus becomes an extension of the optic nerve and an instrument of the soul. The air itself becomes percipient, perceives the object with which it is in contact, and returns its perceptions through the transformed air to the eye and optic nerve and, ultimately, to the soul. The crucial difference between the Galenic and Aristotelian theories is that whereas Aristotle made the medium an instrument of the visible object and assigned the observer a passive role in vision, Galen made the medium an instrument of the eye and soul and ascribed activity to the observer.[7]

But to classify ancient theories of vision in terms of the direction of radiation or the role of the medium in vision is to overlook fundamental aspects of ancient optics—and also to make the debate among the various theories seem trivial and those who debated it for a thousand years look foolish. There is another scheme of classification, based on the aims and criteria of visual theory, which is far more basic and, therefore, more significant. The Euclidean theory was not merely an extramission theory, but, more fundamentally, a mathematical theory of vision. Euclid's purpose was to offer a geometrical explanation of the perception of space, to develop a mathematical theory of perspective in which the visual cone accounts for the localization of objects in the visual field and the apparent size and shape of objects as a function of their distance from the observer and their orientation with respect to the line of sight.[8] Although physical content unavoidably crept in (Euclid apparently regarded the rays as physically real entities), the theory was not designed with physical plausibility in mind; it was intended as a mathematical theory of vision, and it was to be judged by mathematical, rather than physical, criteria.[9]

By contrast, the intromission theory, whether in its atomistic or Aristotelian form, was intended as a causal or physical account of vision; its purpose was to explain in physical (rather than mathematical) terms how the visible qualities of objects are communicated to the organ of sight. It was without mathematical pretensions and was not to be judged by mathematical criteria.[10] Finally, the Galenic theory, though containing a small amount of physical and mathematical content, was concerned principally with the anatomy of the eye and physiology of sight; it was devised by a physician, and it was meant, above all, to satisfy anatomical and physiological criteria and to fulfill medical needs.

The position I wish to defend, then, is that in antiquity and well into the Middle Ages, these three kinds of theory—mathematical, physical, and physiological—defined the principal battle lines within visual theory. And, therefore, the debate between the intromission theory and the extramission theory was not merely a debate over the direction of radiation, for it was thoroughly intertwined with basic questions about the aims and criteria of optical theory. The intromission theory was by definition a physical or causal theory, defended by physicists or natural philosophers, and its failure on mathematical grounds was (in the view of its practitioners) of little consequence. The extramission theory, by contrast, was a mathematical theory in its Euclidean form, and, thus, immune to criticism on physical grounds, or a physiological theory in its Galenic form, designed with anatomical and physiological ends in view. The question facing visual theory, therefore, was not primarily "In which direction does the radiation proceed?" but "What criteria must a theory of vision satisfy?" And answering this latter question clearly required an investigation of the very foundations of optics.

Visual Theory in Medieval Islam

Much of the Greek achievement in optics was translated into Arabic in the course of the ninth century A.D., and almost immediately the various Greek optical traditions were reproduced on Islamic soil. The mathematical theory of Euclid and Ptolemy, built around the idea of visual rays issuing forth in conical form, was developed and defended by al-Kindi (d. ca. 866), an influential natural philosopher associated with the Abbasid court at Baghdad. Al-Kindi expressed his conclusions in an influential book (entitled *On Vision*), which circulated widely in Islam and later in Latin translation in the West.[11] Al-Kindi's exact contemporary Hunain ibn Ishaq, also associated with the court at Baghdad and himself one of the most important translators, adopted the Galenic theory of vision and disseminated it to a wider public in his *Ten Treatises on the Eye* and *Book of Questions on the Eye*.[12] Finally, the intromission theory of Aristotle found several supporters in the tenth century (including al-Razi and al-Farabi) and in the eleventh century received a full and elaborate defense by the Persian physician and philosopher Avicenna (980–1037).[13] In these newly founded Islamic traditions Greek arguments were in many cases refined and articulated, but the location and shape of the battle lines remained unchanged.

A new theory of vision having broader aims made its first appearance in the eleventh century. It was formulated by Alhazen (Ibn al-Haytham), the great mathematician, astronomer, and natural philosopher who was born about 965 in Basra (near the Persian Gulf) and later emigrated to Egypt, where he died about 1039. Alhazen's achievement was to break out of the limitations of the Aristotelian, Galenic, and Euclidean theories (each with its narrow view of the aims of optical theory) and to formulate a new intromission theory of vision that would simultaneously satisfy mathematical, physical, and physiological criteria. To reveal the difficulty of this task, let me call attention to a few of the obstacles.

Before Alhazen there were, as I have indicated, two versions of the intromission theory—Aristotle's mediumistic version and the atomistic theory of *eidola*—but neither of them provided an adequate account of the communication of visible qualities to the eye. According to the Aristotelian theory, colored bodies produce qualitative changes in all parts of the transparent medium to which they have rectilinear access. But then each part of the eye should be affected by the color of every object (and, indeed, every part of every object) in the visual field, and the result should be complete mixing and total confusion. How then is the observer able to perceive individual shapes and to discern one object off to the right, another straight ahead, and yet a third over on the left? Or to rephrase the objection, if the eye "becomes the visible object," which object (or which part of which object) in the visual field shall it become?[14] The theory fails on mathematical grounds, for it cannot explain those features of visual perception that the Euclidean theory accounted for with its visual cone.

The atomistic theory was equally defective. *Eidola* must apparently radiate from every object in such a way as to enter the pupils of a multitude of observers located in different places all at the same time —quite an impossible feat in the view of the theory's critics. Moreover, if the object is large, its *eidola* must shrink in order to enter the observer's eye, and, indeed, they must shrink exactly according to the laws of perspective if they are to account for the facts of visual perception. And once they have so shrunk, how can one know the true size of the object from which they emanated? This theory, too, fails on mathematical (not to speak of physical) grounds. Some of the objections against it were summarized by Hunain ibn Ishaq:

> All people acknowledge and agree that we see only by the hole which is in the pupil. Now if this hole had to wait until something coming from the [visible] object reached it, or a power . . . , or a form, an outline or a quality, as some people maintain, we should not know, in looking at an object, either its extent or its volume. . . . Its entering into the eyes is something which reason does not comprehend and of which nobody has ever heard, for according

> to this hypothesis a complete form or outline of the viewed object would necessarily reach and enter into the eye of the beholder at the same moment. Supposing then that a great many people looked at it, say, for example, ten thousand persons, it would have to return to the eye of every one of them, and its form and outline would have to enter completely into them. But this is far from probable and must therefore be ranked among the untenable hypotheses.[15]

Hunain's arguments against the intromission theory were buttressed by those of his contemporary al-Kindi. Al-Kindi had a variety of objections to the intromission theory, but one in particular that reveals the magnitude of the difficulties facing Alhazen. Al-Kindi's position was that the perception of shape could be adequately explained only by the extramission theory. According to any of the intromission theories,[16] in his view, a circle situated edgewise before the eye would send its form or image (representing the entire circle) to the eye.[17] It is difficult to know exactly how al-Kindi conceived this transmission of forms or images in the intromission theory, but presumably they were thought to pass as coherent units through the space (or medium) between the object and the observer, maintaining the same edgewise orientation as the object from which they issued. (Figure 26

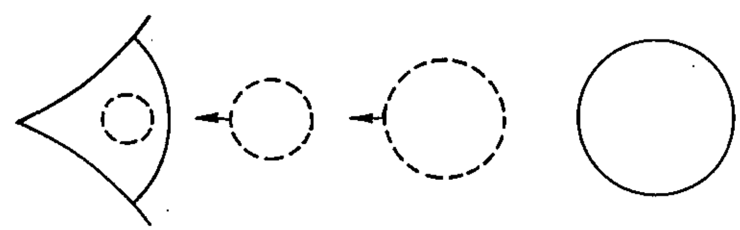

Fig. 26 Al-Kindi's interpretation of the radiation of forms according to the intromission theory.

is a rough attempt to sketch al-Kindi's view of the transmission of forms in the intromission theory.) Once inside the eye, the forms would be surrounded by the visual power and would therefore be perceived in their full circularity. However, all of this is contradicted by simple observation: in truth, a circle situated edgewise before the eye is perceived only as a line, and the intromission theory (since it makes predictions that conflict with the facts of observation) must be false. Al-Kindi's position, then, is that the intromission theory is proved false because it is incompatible with the laws of perspective.[18]

Of course, neither Aristotle nor the atomists had defended a conception of the radiation of forms or the perception of shape quite like the one al-Kindi attributed to them. However, al-Kindi was not far off on the atomists, whose theory could easily enough receive his interpretation. Aristotle had altogether ignored the problem of perceiving shapes; therefore, although he would undoubtedly have denied al-Kindi's interpretation of his theory, he had no alternative to offer. What is important about al-Kindi's argument, then, is that it reveals the inability of the intromission theory, in any of the forms in which it had thus far been articulated, to account for the perception of shape. If shapes were to be perceived by a process of intromission, it seemed necessary that there be a coherent process of radiation, by which a form or image bearing the shape of the object passed as a single unified entity to the observer's eye; but such an intromission theory was vulnerable to the objections raised against it by al-Kindi and Hunain. It is apparent that a new kind of intromission theory was required—one in which radiation into the eye would no longer be conceived as the transmission of coherent forms.

It is ironic that this new kind of intromission theory would be erected by Alhazen on a principle first stated by al-Kindi (but in a different context, not directly related to vision). Al-Kindi argued that radiation does not issue from the surface of a luminous body as a whole; rather, each point on the surface radiates light in all directions independently of other points (see fig. 27).[19] This may seem like a trivial and self-evident claim, and although al-Kindi was the first to state it clearly and explicitly, it is perhaps implicit in earlier writings. But what was surely not trivial or self-evident was the position taken by Alhazen, namely, that upon this punctiform analysis of the visible object one could build a successful intromission theory of vision. What would surely have been taken for granted by all of Alhazen's predecessors or contemporaries is that in any intromission theory a coherent visual impression can result only from a coherent process of radiation.

The obstacles facing anybody who would maintain the contrary are easily revealed. If, in fact, every point of the visible object radiates in all directions, then every point in the eye should be affected by light and color from virtually every point in the visual field, and the outcome should be total confusion. Figure 28 reveals the mixing, within the eye, of rays issuing from the endpoints of the visible object.[20] To explain vision as we know it, there must be a one-to-one correspondence between points in the visual field and points in the eye—so that every point in the eye is stimulated by one point in the visual field, and the pattern of the visual field is reproduced in the eye. But on al-Kindi's theory of incoherent punctiform radiation, which Alhazen

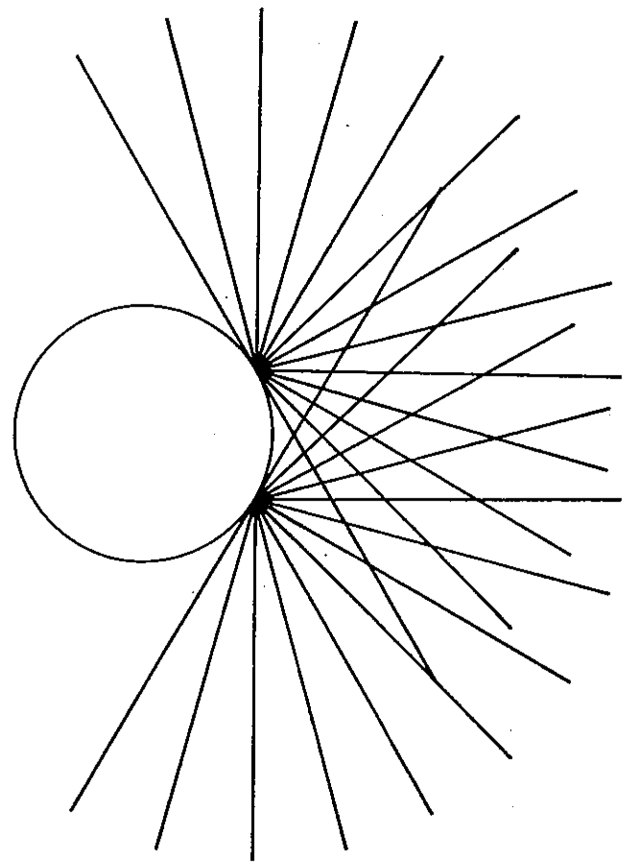

Fig. 27 Incoherent radiation from two points of a luminous body.

hoped to use as the basis of his intromission theory of vision, a one-to-one correspondence seems beyond the realm of possibility.

Alhazen undertook to solve this problem in his largest optical work, the *Kitab al-Manazir* (translated into Latin as *De aspectibus* or *Perspectiva*). He recognized there that every point in the eye receives a ray from every point in the visual field. But only one ray falling on each point of the surface of the eye is incident perpendicularly; or to turn the geometry around, from each point in the visual field there falls only one ray perpendicular to the convex surface of the eye. All other rays, falling obliquely on the surface of the eye, are refracted; and as a result of refraction they are weakened to the point where they are incapable of stimulating the visual power.[21]

But what is of crucial importance is that these perpendicular rays constitute a pyramid or cone, with the object or visual field as base and the center of the eye as apex. Because the rays are rectilinear and converge toward a single apex, they maintain a fixed arrangement and fall on the crystalline humor (or lens) of the eye in precisely the same order as the points in the visual field from which they originated (see fig. 29). They stimulate the visual power residing in the crystalline lens, thus producing visual perception.[22] To be sure, difficulties remain. To mention only the most serious, is it really justifiable to ignore all refracted rays? Refraction may well be held to weaken rays, but why should only slightly refracted (and therefore only slightly weakened?) radiation be totally incapable of stimulating the visual power? Alhazen did not make a convincing case at this point, and it was to remain one of the principal weaknesses of the theory until resolved by Johannes Kepler early in the seventeenth century.[23]

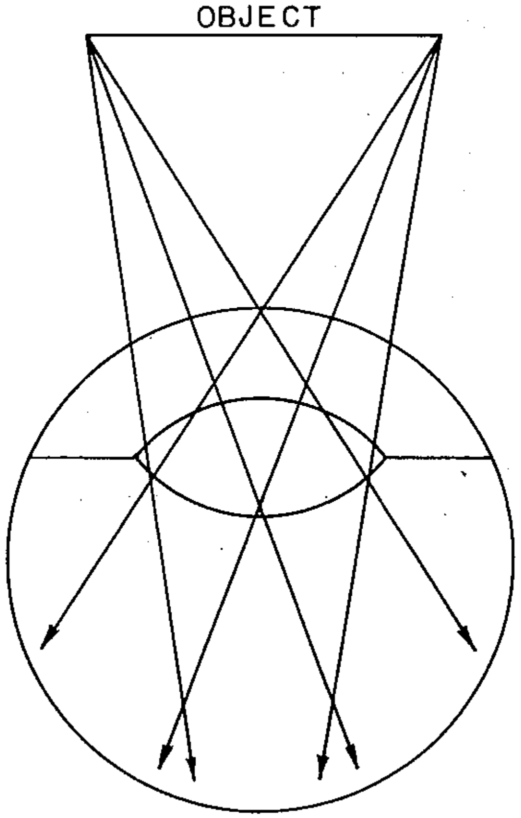

Fig. 28 Mixing, within the eye, of rays from the endpoints of a visible object.

Nevertheless, Alhazen made a most important contribution to visual theory. He formulated an intromission theory which, despite certain difficulties, proved capable of explaining the principal facts of visual perception: it explained physical contact between the object and observer through the intromitted rays, and through its visual

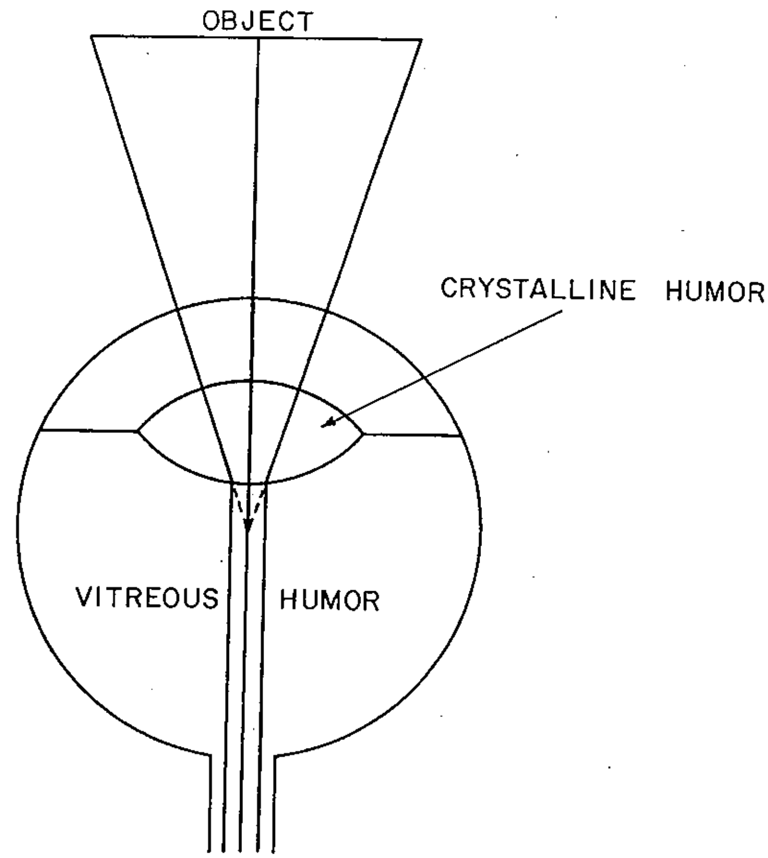

Fig. 29 The geometry of sight according to Alhazen.

cone explained the perception of shape and accounted for the laws of perspective. It thus achieved a level of success not attained by any previous intromission theory, and largely through Alhazen's influence (aided by the considerable weight of Aristotle's authority), the intromissionist character of vision would never again be seriously doubted.[24] Alhazen also established punctiform analysis of the visible object and the need for a one-to-one correspondence between points in the visual field and points in the eye as permanent and essential elements of the intromission theory—thus providing the basic framework of visual theory that has prevailed until the present.

But to say no more would be to miss the main point of Alhazen's achievement. He did not merely establish the intromission theory of vision beyond dispute and contribute many of its essential characteristics, but did so in such a way as to obliterate the old battle lines and fundamentally alter the aims and scope of optical theory. Like all intromission theories, Alhazen's gave an adequate *physical* or *causal* account of the communication of the visible qualities of the object to the observer: the "forms" that emanate from each point of the visual field communicate to the observer, apparently through some kind of modification of the medium, the pattern of light and color. But, in addition, Alhazen successfully incorporated into his intromission theory the visual cone of the extramissionists. By restricting himself to perpendicular rays, he appropriated the Euclidean visual cone and, hence, the entire *mathematical* achievement and *raison d'être* of the extramission theory. And, finally, although I do not have space to go into the matter here, Alhazen embraced the *anatomical* and *physiological* claims of the medical tradition and integrated them into his theory. What Alhazen thus achieved was to draw together the mathematical, physical, and medical traditions into a single comprehensive theory, which satisfied the criteria of all of the traditions. He was neither Euclidean nor Aristotelian nor Galenist—or else he was all three of them. He created a new optical tradition and established the aims and criteria of optics which would prevail, though not without rivals, until Kepler and beyond. Although containing traditional materials at every point, the resulting edifice was a fresh creation.

OR

Visual Theory in Medieval Christendom

While al-Kindi and Alhazen were reconstructing visual theory in the Islamic world, the West was still struggling to retain and assimilate remnants of the Greek achievement. The Platonic theory of vision (received largely through Chalcidius's translation, early in the fourth century, of the first half of Plato's *Timaeus*) dominated until the thirteenth century. Plato's stress on the visual fire emanating from the observer's eye (coupled, of course, with external illumination and light or fire from the observed object) was reinforced by St. Augustine, who also taught an extramission theory. However, in the twelfth and thirteenth centuries virtually the full corpus of Greek and Islamic works on optics became available in translation; and this vastly complicated the situation, for the West now had at its disposal a large group of venerable (and, therefore, authoritative) works, which taught every conceivable theory of vision. Plato, Aristotle, Euclid, Galen, Augustine, al-Kindi, Alhazen, Avicenna—all were known, and all had reached different conclusions on the subject of vision. The task facing scholars of the thirteenth century was to sort out, make sense of, and, if possible, reconcile the various elements of this optical heritage.

The key figures in the process were Albertus Magnus (the teacher of Thomas Aquinas) and Roger Bacon.[25] Albertus (d. 1280) was the first great Western expositor of the whole Aristotelian corpus (which, except for logic, was largely unknown before the translations of the twelfth and thirteenth centuries), and in the 1240s and 1250s he turned his attention to those Aristotelian books that touched upon visual theory. He wrote a long refutation of the extramission theory and in its place attempted to establish the Aristotelian doctrine that vision is caused by an alteration of the transparent medium by a visible object, and the propagation of this alteration to the watery substance of the eye. However, Albertus added several non-Aristotelian embellishments, including the Galenic emphasis on the crystalline humor as the seat of the visual power and the Euclidean visual pyramid.[26] Nevertheless, Albertus remained principally an Aristotelian, and it was chiefly he who established the Aristotelian theory as a major force in the West.

Through the influence of Albertus and others, Aristotelian philosophy in general came to dominate the arts curriculum in the medieval university. By the second half of the thirteenth century, an arts student at Paris could not receive the M.A. degree without hearing lectures on all available Aristotelian works, and by the fourteenth century large numbers of masters were turning out commentaries on Aristotle's *De anima*, *De sensu*, and *Meteorologica*—works in which one could hardly avoid discussing visual theory. As a result, the Aristotelian theory of vision rose to a position of dominance, for it was virtually impossible to comment on the Aristotelian texts (especially *De anima* and *De sensu*) without concluding that Aristotle's arguments had demolished the extramission theory and that his own intromission theory satisfactorily accounted for the known facts of visual perception (if one ignored mathematics and physiology, as Aristotelians usually did).

The second major tradition of visual theory in the West was founded by Roger Bacon (d. ca. 1292), who took up the study of optics early in the 1260s, about the time Albertus's interest in optics was subsiding. But whereas Albertus had been a disciple of Aristotle, Roger became the disciple of Alhazen.[27] He argued that forms (or "species," as he called them) issue from each point or small part of the visible object, enter the observer's eye, and arrange themselves on the surface of the crystalline humor in the same order as the points in the visual field from which they issued. Moreover, nonperpendicular rays were to be ignored because they are weakened through refraction and do not stimulate the visual power. Bacon followed Alhazen in many other details, but it must suffice to insist that he reproduced all of the essential aspects of Alhazen's theory of vision and also adopted Alhazen's view of the aims and scope of visual theory.

However, Bacon also fancied himself the disciple of everybody else who had written on the subject. He was deeply convinced of the unity of all knowledge and the fundamental agreement of the ancient sages, and he was therefore committed to showing that all who had addressed themselves to the subject of vision had been of one mind; he would conciliate among Aristotle, Euclid, Ptolemy, Augustine, Alhazen, Avicenna, and the rest in order to reveal the underlying unity of their thought. This was by no means an impossible task. Insofar as the mathematicians had simply devised a mathematical theory of perspective, they had treated a topic ignored by Aristotle and the natural philosophers or physicists; by the same token, the natural philosophers had focused on causal issues, and the physicians on questions of anatomy and physiology. The three major traditions might thus appear complementary, and a merger along the lines suggested by Alhazen would appear quite sufficient. However, there were some points of disagreement that could not be lightly dismissed: the mathematicians had made physical claims about the nature and direction of radiation, natural philosophers had occasionally touched upon the mathematics of the visual process, and Alhazen had addressed himself not only to the mathematics and physics of vision, but also to its anatomy and physiology. Thus, if Bacon wished to demonstrate that all were in agreement, some ingenious argumentation would be required.

One point of disagreement calling for Bacon's attention was the physical nature of the radiation responsible for sight. Here he was faced with Aristotle's theory of the qualitative transformation of the medium, Alhazen's discussion of the forms of light and color, and the Neoplatonic doctrine of the multiplication of species defended earlier in the thirteenth century by Robert Grosseteste. Bacon's procedure in this case was simply to overlook the differences—to take Grosseteste's species,[28] endow them with all of the mathematical properties of Alhazen's forms, and to claim that this was what Aristotle had meant all along. In the finished theory, each point of an object was held to produce a likeness of its light and color in the adjacent transparent medium, which, in turn, produced a further likeness in the next part of the medium, and so forth:

> But a species is not body, nor is it moved as a whole from one place to another; but that which is produced [by an object] in the

> first part of the air is not separated from that part, since form cannot be separated from the matter in which it is unless it should be mind; rather, it produces a likeness to itself in the second part of the air, and so on. Therefore there is no change of place, but a generation multiplied through the different parts of the medium; nor is it body which is generated there, but a corporeal form that does not have dimensions of itself, but is produced according to the dimensions of the air; and it is not produced by a flow from the luminous body, but by a drawing forth out of the potentiality of the matter of the air.[29]

This is Bacon's doctrine of the multiplication of species. It is Aristotelian in its utilization of the matter-form dichotomy and its stress on the transformation of the medium. It harks back to Grosseteste in its choice of terminology and in its acknowledgement that the species of light and color are instances of a more general radiation of force or power throughout the universe. And it assigns to species all of the properties, mathematical and physical, of Alhazen's forms; indeed, Bacon was careful to employ Alhazen's terminology along with that of Grosseteste and to claim that Alhazen's "forms" and Grosseteste's "species" are one and the same thing.

A second point of conflict among the inherited theories, which demanded Bacon's attention, was the direction of radiation. Here was a matter addressed by every author who had written on the subject of vision, and it would be no trivial achievement to demonstrate that all had really been saying the same thing. Bacon approached the problem by affirming, with Aristotle, Alhazen, and the other intromissionists, that vision is basically the result of intromitted rays. But he then argued that although intromitted rays are necessary for vision, and, indeed, are the principal agents of vision, they are not alone sufficient for vision. It is necessary also that visual rays or species emanate from the observer's eye to excite or ennoble the medium and the species of the visible object, thereby rendering the latter capable of stimulating sight. Bacon pointed out that Alhazen had not disproved the existence of visual rays, but had only demonstrated their insufficiency as the cause of sight. Bacon was thus able to produce what he regarded as the perfect synthesis among competing schools of thought. Visual rays exist (as maintained by Euclid, Ptolemy, al-Kindi, and Augustine), but they perform none of the functions denied them by the intromissionists. Each school had presented a portion of the truth, and Bacon was convinced that he had now restored truth in its fullness.[30]

Bacon's conclusions were presented in his *Perspectiva* (also issued as part 5 of his *Opus maius*), a book that circulated widely and was responsible, in large part, for originating the tradition of *perspectiva* in the West.[31] Bacon influenced his fellow countryman and Franciscan brother (later Archbishop of Canterbury) John Pecham (d. 1292) and the Silesian scholar Witelo (d. after 1277). Both Witelo and Pecham wrote popular optical texts (Witelo a long one entitled *Perspectiva* and Pecham a short one entitled *Perspectiva communis*) in which the science of *perspectiva* was articulated and disseminated. The perspectivist tradition persisted, though somewhat thinly, in the fourteenth century in three treatises entitled *Questiones super perspectivam* or *Questiones perspective* written by Dominicus de Clavasio, Henry of Langenstein, and Blasius of Parma. Here isolated questions from the science of *perspectiva* were submitted to analysis through the scholastic techniques of disputation. Finally, in the fifteenth and sixteenth centuries *perspectiva* became the subject of lectures at a variety of universities, including Prague, Leipzig, Krakow, Würzburg, Alcalá, Salamanca, Paris, Oxford, and Cambridge.

I have spoken only of the Aristotelian and perspectivist traditions in the West. There were others, of course, but of considerably less significance. The Galenic theory, although it experienced little or no development during the Middle Ages, could always be found in treatises on ophthalmology or general works on anatomy; and in the sixteenth century it benefited from the general revival of anatomical studies and became a significant force. Visual theory also entered into theological treatises and was put to theological use (especially in connection with psychology and epistemology) in ways that probably justify speaking of a theological tradition in medieval visual theory. Finally, the mathematical tradition of Euclid, Ptolemy, and al-Kindi had by no means disappeared; although it is exceedingly difficult to discover a Western defender of the extramission theory in its pure Euclidean form, the works of Euclid, Ptolemy, and al-Kindi had a wide circulation and were apparently being read. However, for most people in the West the label "mathematical theory of vision" no longer signified the Euclidean theory, but the Baconian. The mathematical tradition was now being carried forward by the perspectivists. In truth, the perspectivist tradition was more than mathematics, for the perspectivists were the heirs of Alhazen and were therefore concerned not only with the mathematics of vision, but also with its physics and physiology. But *perspectiva* was the only living optical tradition containing any mathematics, and perspectivists were therefore easily and properly regarded as champions of the mathematical approach.

The struggle over visual theory in the Middle Ages thus ended indecisively. Alhazen's theory of vision, with its broad view of the aims and scope of visual theory, was available in the works of Roger Bacon and his followers. But the members of competing schools had not capitulated to the arguments of the perspectivists, and, indeed, Aristotelians far outnumbered the adherents of any other theory.[32] What is of the utmost importance for the subsequent history of optics, however, is that the perspectivist tradition persisted throughout the medieval period, experienced a revival in the sixteenth century (in the work of Francesco Maurolico, the printing of Witelo's *Perspectiva* in 1535, 1551, and again with Alhazen's *De aspectibus* in 1572, and the appearance of nine printed versions of Pecham's *Perspectiva communis*), and at the beginning of the seventeenth century was seized upon by Johannes Kepler and made the foundation of his new theory of the retinal image. Kepler's achievement was, thus, the culmination of medieval developments. Kepler worked almost entirely within the perspectivist framework, attempting to build an intromission theory of vision on the punctiform analysis of the visible object.[33] He responded to the problem the perspectivists had raised, seeking a mechanism (involving refraction) by which to deal with the superfluity of rays emanating from a given point in the visual field and to establish a one-to-one correspondence between points in the visual field and points in the observer's eye. Most significantly, Kepler's conception of the scope of visual theory—his concern with the mathematics, physics, and physiology of the visual process—was taken over from the perspectivists.

There were, of course, new elements in Kepler's thought, such as the sensitivity of the retina.[34] And it is surely not in dispute that Kepler presented a new and more satisfactory answer to the question of how one sees. He argued that if all rays entering the eye are vision-producing (that is, if nonperpendicular rays must be taken into account along with perpendicular rays), then a one-to-one correspondence can be established only if all rays issuing from a given point in the visual field are returned, through refraction in the humors of the eye, to a point of focus on the retina. The result will be an inverted image of the visual field, a *pictura*, on the surface of the retina (see fig. 30).[35] But clearly this was the answer to a question with which scholars had been struggling for nearly 600 years—a new answer to a medieval question, designed to satisfy the criteria of the medieval perspectivist tradition.

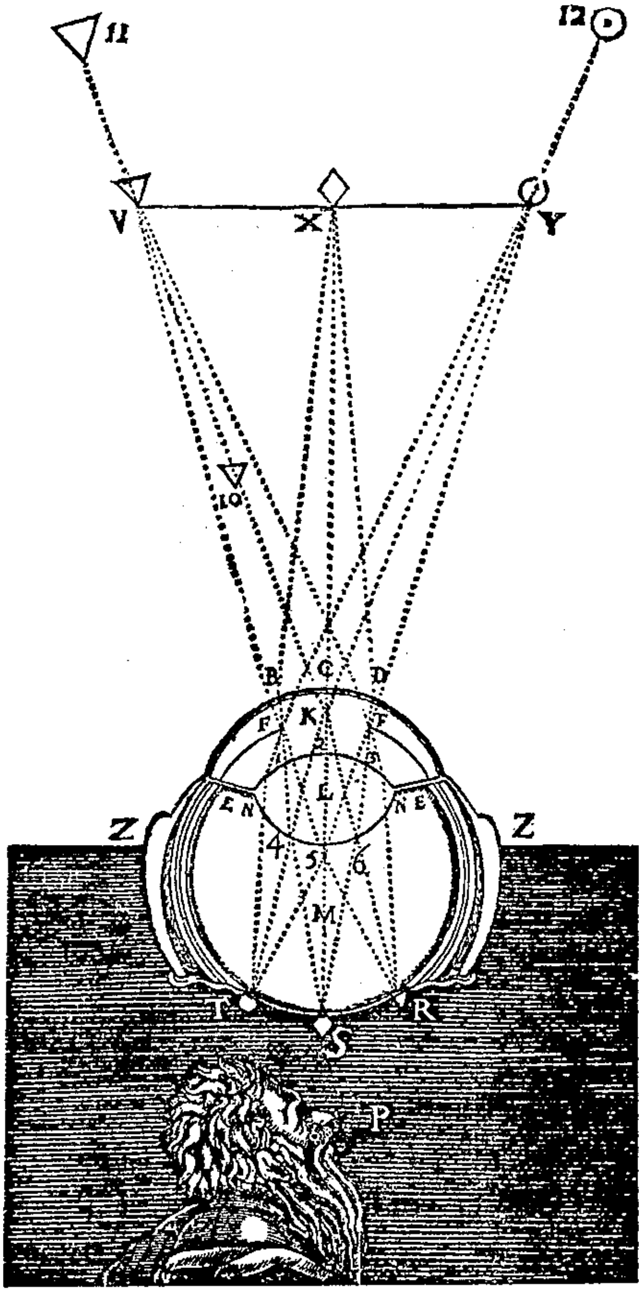

Fig. 30 Descartes' illustration of the theory of the retinal image.

The Nature and Propagation of Light and Color

If vision was one of the central themes of medieval optics, a topic that attracted equal attention was the nature and propagation of light and color. The distinction between light and color was universal in early optical thought, each being regarded as a property or quality of visible objects. In antiquity, light was often associated with fire or the luminosity of fiery bodies such as the sun, while color was associated with the quality of nonluminous objects that makes them visible. This conception of light and color (greatly refined and extended) lies behind Aristotle's definition of light (*phos*) as a state of the transparent medium resulting from the presence of fire or some other luminous body—more specifically, the actualization of the transparency of the medium, the achievement of that state in which transparency is no longer merely potential, but actual, so that bodies separated from the observer by the medium are visible. As for color, Aristotle defined it as that which overlies the surface of visible objects and has the power to set in motion (or produce qualitative changes in) a medium whose transparency has already been actualized. Thus, in Aristotle's scheme light is not itself visible, but signifies a state of the medium that makes colored bodies on the other side of it visible; color, rather than light, is the "proper object" of sight.[36]

Most Muslim scholars who discussed the matter adopted some variation of the Aristotelian theory of light and color. Avicenna, for example, accepted Aristotle's distinction between light and color and agreed that light is a quality of the transparent, while color is a quality of opaque bodies. However, within the category of "light" Avicenna distinguished among (1) the brightness that one observes in fire or the sun (*lux* in the Latin translation of Avicenna's work), the luminous quality of fiery objects by which (when a transparent medium intervenes) they themselves are perceived; (2) the splendor (*lumen*) shining from luminous bodies, which falls on nonluminous objects and causes them to be visible (*lumen* might be thought of as the effect of *lux* on the adjacent medium and surrounding objects); and (3) the ray (*radius*) or radiance (*radiositas*), which Avicenna defined as "that which appears around bodies . . . as though it were something emanating from them."[37] Avicenna added that colors exist only in potentiality when unilluminated and unobserved: "white is not white and red is not red unless we see them, and we do not see them unless they are illuminated."[38]

If Avicenna's contemporary Alhazen consistently distinguished between *lux* and *lumen*, the fact was certainly obscured by the Latin translation of his book, where *lux* and *lumen* appear to be used interchangeably. Terminology aside, however, Alhazen surely made the same conceptual distinction. He argued that vision is produced when the form of light (usually *lux* when employed in this phrase) and the form of color enter the observer's eye and encounter the visual power; and it would have been perfectly obvious to any of Alhazen's Western followers that his "form of light" was identical to Avicenna's *lumen.* What is much more significant about Alhazen's theory, however, is that it makes light or *lux* an object of vision along with color, altering its status from a state of the medium required for the perception of color to a quality of luminous objects that is itself perceived.[39] Alhazen maintained that both light and color propagate their forms independently through the medium, although forms of the two kinds are propagated identically and, therefore, may become intermingled and stimulate the visual power together.[40] Alhazen also distinguished between the "essential" light of self-luminous bodies and the "accidental" light of opaque or transparent bodies that have received illumination from another source. Opaque or transparent bodies (in A. I. Sabra's words) "take possession of the light shining upon them and, having made it their own, they in turn shine as if they were self-luminous."[41]

The themes treated by Avicenna and Alhazen underwent continued development in the West. Avicenna's distinction between *lux* and *lumen* was widely employed, though (with the encouragement of Alhazen) it was widely ignored.[42] It was agreed by virtually everybody who touched upon the matter, however, that both light (usually *lux*) and color propagate their forms or likenesses through transparent media to observers. The problem that provoked the most interest and discussion was the physical nature of this propagation and the status of light and color in the medium. It was obvious that light and color (or their forms) had to pass through the medium if one were to explain visual perception; yet if the observer looked *at the medium*, rather than at the object *through the medium*, the medium did not seem luminous or colored at all—but merely transparent. Moreover, different colors could apparently occupy the same place in the medium (as when the lines of sight of two observers cross) without mixing or interference. The Spanish Muslim Averroes (d. 1198) had attempted to account for these curious facts by employing a distinction between the spiritual and the corporeal existence of light and color: in the soul, he had argued, light and color (or their forms) have a spiritual existence; in the transparent medium, an existence intermediate between the spiritual and the corporeal:

> As for those who are of the opinion that the forms of sense-objects are imprinted upon the soul in a corporeal manner, the absurdity of their view can be demonstrated by the fact that the soul can receive the forms of contraries at the same time, whereas if they

> were bodies, this would be impossible. This will occur not only in the case of the soul but also in the case of media, for it is apparent that in the same space of air, the organ of sight can receive two contrary colors at the same time, as when it regards two individual things, one white and the other black. Furthermore, the fact that large bodies can be perceived by the sight through the pupil of the eye, despite its being small, . . . is proof that colors and whatever is connected with them are not conveyed to the sight materially but rather spiritually. . . . The existence of forms in media is of a kind intermediate between the spiritual and the corporeal. This is true for the reason that the existence of forms outside the soul is completely corporeal; consequently, their existence in the medium is in an intermediate stage between the spiritual and the corporeal.[43]

By "spiritual existence" Averroes meant simply existence that does not involve matter (exemplified, for example, by the immaterial celestial intelligences), so that such features of the material world as interference and mixing do not apply. How we are to conceive existence intermediate between the spiritual and the corporeal (an extremely subtle or diaphanous state of being?), Averroes does not explain.

Averroes' solution was well known and much discussed in the West.[44] Albertus Magnus, after a long and intricate discussion of what it meant for light and color (or their species) to be in the medium, concluded that in some sense they are there corporeally; as for Averroes, Albertus pointed out that he can be interpreted to have meant simply that light and color exist in the medium with extreme rarity or subtlety or that the species of color exists in the medium without the material causes that originally generated the color in its subject and without the matter of the subject.[45] Most thirteenth-century natural philosophers reached a similar conclusion. Roger Bacon argued that what is propagated is a species, a likeness or corporeal form, which is called forth successively out of the potentiality of the transparent medium; and as a corporeal form it has, of course, corporeal or material existence in the medium.[46] In the fourteenth century the problem was attacked from a wide variety of perspectives and with great subtlety. The extreme position was adopted by William of Ockham (d. ca. 1349), who dispensed altogether with species or any other intermediary between object and sense organ and embraced the idea of action at a distance. The object, he argued, can impress in the eye a quality or likeness of itself without in any way affecting the intervening medium. In defense of such an extraordinary claim, Ockham pointed out that there is no experiential evidence for the existence of species, since we have no awareness of them but posit them solely to explain our awareness of the object. However, it is unnecessary to posit species in order to explain our awareness of the object, since the object (which is disposed to act on the visual power) and the visual power (which perceives when acted upon) are sufficient by themselves to account for visual perception.[47]

To a student of modern physical optics, the medieval analysis of the physics of the propagation of light and color must surely appear futile and incomprehensible; spiritual versus corporeal existence and the *lux-lumen* distinction are not part of his idiom. But such was the nature of the medieval optical enterprise. However, the propagation of light and color could also be approached mathematically, and here the medieval and the modern theory more nearly coincide. The foundation of the mathematical approach, then as now, was the rectilinear propagation of light and color, assumed in antiquity by Euclid and perhaps demonstrated by Ptolemy.[48] During the Middle Ages the rectilinearity of light was accepted without serious question, though Alhazen (in a portion of his book never available in Latin) also supplied an experimental demonstration of the fact.[49] If light (or its form or species) is propagated in straight lines, then, of course, its path can be represented by a linear ray, and on this foundation an elaborate system of ray geometry can be erected. But ray geometry also requires an understanding of the principles of reflection and refraction. In antiquity, and, subsequently, in the Middle Ages, the law of reflection was fully and correctly grasped: the incident and reflected rays form equal angles with the reflecting surface, and the plane formed by the incident and reflected rays is perpendicular to the reflecting surface (or its tangent). As for refraction, it was established in antiquity and well known during the Middle Ages that a ray passing obliquely from a less dense to a more dense medium is refracted toward the perpendicular to the refracting interface, while a ray passing in the opposite direction is oppositely refracted. It was also recognized that the image of a visible point seen by reflection in a mirror or by refraction through a transparent interface will appear to be located where the rectilinear extension of the ray incident on the eye (in the intromission theory, or emerging from the eye in the extramission theory) intersects the perpendicular dropped from the visible point to the reflecting or refracting surface. For example, point *B* (fig. 31) submerged in water will appear to observer *A* to be located at *L*, where perpendicular *BD* dropped from the visible point to the refracting surface intersects the rectilinear extension of ray *CA* incident on the observer's eye.[50]

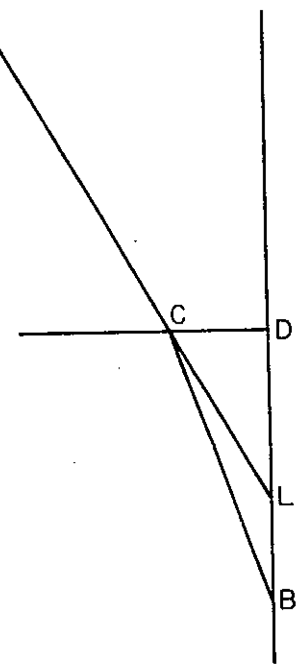

Fig. 31 A point viewed by refraction at a plane interface.

There were several attempts to supply quantitative data on refraction and even to establish a quantitative law of refraction. Ptolemy had sought such a law, and he bequeathed his numerical data to the Middle Ages.[51] This data was reproduced in the thirteenth century by Witelo, who also attempted to extrapolate Ptolemy's data to cover refraction in the reverse direction; however, it was Witelo's misfortune to misunderstand the reciprocal character of refraction (that refracted light will retrace the same path if its direction is reversed), and, consequently, he presented absurd and impossible results.[52] A quantitative law was also attempted by Robert Grosseteste early in the thirteenth century, but this amounted merely to the claim (based, undoubtedly, on principles of symmetry and simplicity) that as light passes from a less dense to a more dense medium its angle of refraction is half its angle of incidence.[53]

Employing the principle of rectilinear propagation and the laws of reflection and refraction, Alhazen and the perspectivists in the West were able to perform some remarkably sophisticated ray geometry. They could, for example, determine image locations for objects viewed in mirror surfaces or through transparent interfaces of plane or spherical figure. They analyzed in more limited fashion mirrors of conical, cylindrical, and paraboloidal form, and in some instances they were able to deal correctly with the phenomena associated with the focal point or focal plane of a mirror. To give only a single illustration, Witelo demonstrated that the image of *DE* (fig. 32) viewed by reflection in a concave spherical mirror by eye *B* will appear at *LN*, where the reflected rays (*AB* and *GB*) incident on the eye intersect *DM* and *EM*, the perpendiculars to the reflecting surface drawn from

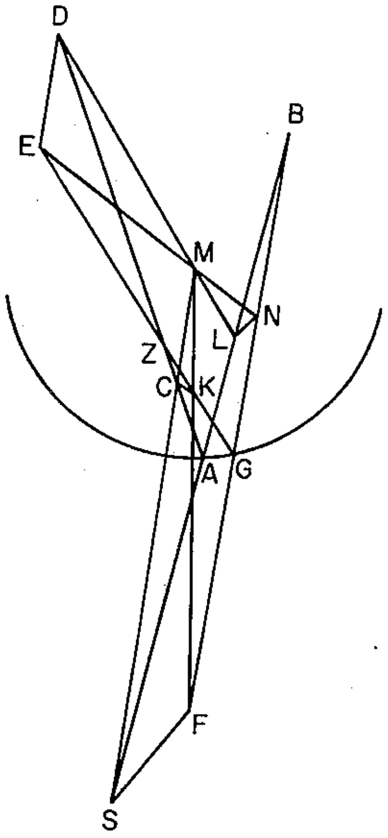

Fig. 32 Image-formation in a concave spherical mirror.

the end points of the object. If, on the other hand, the object should be located at *CK* (between the mirror and its focal point), its image will be at *SF*, where the extension of the reflected rays (*AB* and *GB*) incident on the eye intersect perpendiculars *MC* and *MK*. Note that Witelo appears to understand implicitly that image *SF* is erect and virtual, while image *LN* is inverted and real.[54] Medieval scholars did not develop a theory of lenses; refraction at a single interface was analyzed with skill and sophistication, and the basic focusing properties of the burning sphere were understood, but that is as far as the matter went. It was not the principles of optical instruments that were being sought, but an understanding of the laws of nature, applied to the most general cases; medieval optics was not an instance of applied science, but of natural philosophy.

A final achievement of medieval geometrical optics (this in the realm of meteorology) must be mentioned, if only because it has been so celebrated. The rainbow had attracted the attention of natural philosophers in antiquity and continued to do so during the Middle Ages. Aristotle had devoted a substantial portion of his *Meteorology* to the subject, arguing that the rainbow results from the reflection of visual radiation from droplets of moisture in a cloud to the sun,[55] and some form of this reflection theory was dominant throughout the Middle Ages. However, in the thirteenth century Robert Grosseteste attempted to bring refraction into the theory, and although his own theory remains incomprehensible, it was common thereafter to employ some combination of reflection and refraction to account for the rainbow. Witelo, for example, argued that solar light is refracted by drops in a mist and then reflected to the observer's eye by the convex surface of drops deeper within the mist.[56]

However, early in the fourteenth century Theodoric of Freiberg (d. ca. 1310) presented a theory that closely resembles the modern theory, wherein solar radiation enters an individual raindrop by refraction, undergoes either one or two reflections at the rear surface of the drop (one reflection to produce the primary rainbow, two reflections to produce the secondary bow), and is then refracted once more as it emerges from the drop and proceeds to the observer's eye. Figure 33 illustrates the path of the radiation through a single drop for the primary rainbow.[57] Figure 34 illustrates the production of the primary rainbow by a collection of raindrops.[58] Theodoric claims to have performed experiments with prisms and transparent crystalline

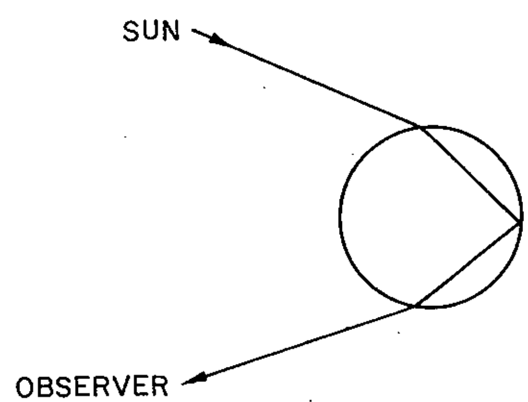

Fig. 33 Production of the primary rainbow: radiation through a single raindrop.

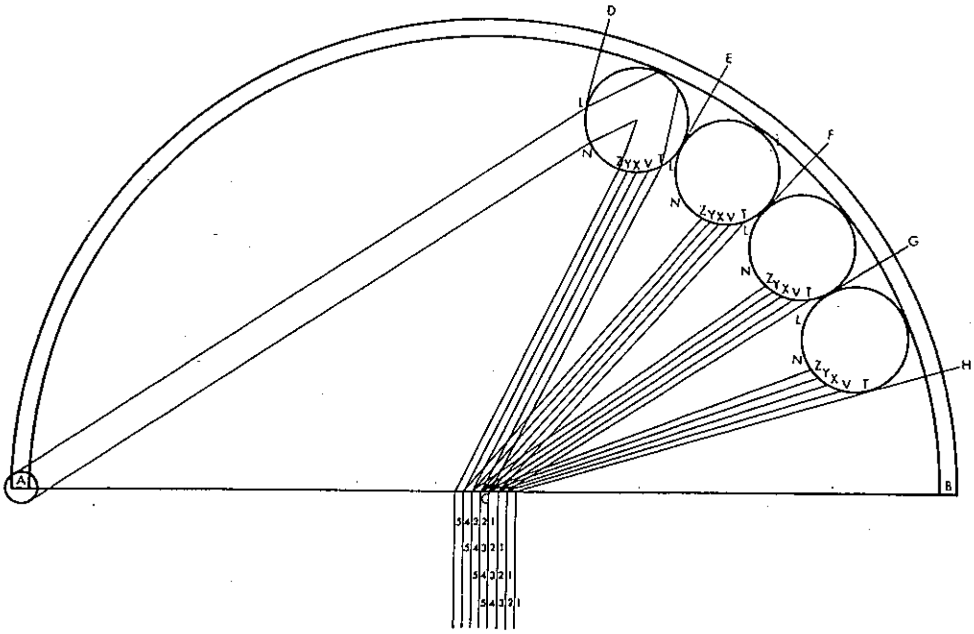

Fig. 34 Theodoric of Freiberg's theory of the primary rainbow.

spheres to confirm his theory, and it is, indeed, a remarkable achievement of the perspectivist tradition. However, to his contemporaries it seemed no more plausible than the alternatives, and it was not widely known or discussed during the Middle Ages. Finally, in the seventeenth century René Descartes presented virtually the same theory, and it is through him that the theory has come down to us.[59]

Notes

1. The ideas presented in this and the next two sections are developed and defended at much greater length in my *Theories of Vision from al-Kindi to Kepler* (Chicago, 1976).

2. "Letter to Herodotus," in Diogenes Laertius, *Lives of Eminent Philosophers* 10. 48–49, trans. R. D. Hicks, vol. 2 (London, 1925), pp. 577–79.

3. *De rerum natura* 4. 54–61.

4. On Epicurean *eidola* see also Edward N. Lee, "The Sense of an Object: Epicurus on Seeing and Hearing," in *Studies in Perception: Interrelations in the History of Philosophy and Science*, ed. Peter K. Machamer and Robert G. Turnbull (Columbus, Ohio, 1978), pp. 29–30, 42–50.

5. On the Euclidean and Ptolemaic theories of vision, see Albert Lejeune, *Euclide et Ptolémée: Deux stades de l'optique géométrique grecque*

(Louvain, 1948). Euclid believed the visual cone to consist of discrete rays separated by spaces; Ptolemy considered it a continuum.

6. For Aristotle's theory, see his *De anima* 2. 7, 418a26–419a25; *De sensu* 2–3, 437a18–439b18. See also below, n. 55.

7. Aristotle's theory of vision might thus be viewed as an intromission version of the mediumistic theory, while Galen's can be viewed as an extramission version of the mediumistic theory. The fullest account of Galen's theory of vision is in Rudolph E. Siegel, *Galen on Sense Perception* (Basel, 1970); however, this work must be used with caution.

8. The location of an object within the visual field is determined by the location within the visual cone of the rays incident upon it, and the apparent size of a visible object is a function of the angle between rays issuing to its extremes.

9. Euclid's most prominent followers, Ptolemy and al-Kindi, added physical content to the Euclidean theory, but its aims remained principally mathematical.

10. For example, it made no attempt to explain how various objects or visible points are perceived at particular places within the visual field.

11. On al-Kindi's theory of vision, see Lindberg, *Theories of Vision*, chap. 2; also Lindberg, "Alkindi's Critique of Euclid's Theory of Vision," *Isis* 62 (1971):469–89.

12. Hunain translated Galen's *De usu partium* and *De placitis Hippocratis et Platonis*, the two works from which he drew most of his material on vision. An English translation of Hunain's *Ten Treatises* is available in *The Book of the Ten Treatises on the Eye Ascribed to Hunain ibn Is-hâq (809–877* A.D.), ed. and trans. Max Meyerhof (Cairo, 1928).

13. See David C. Lindberg, "The Intromission-Extramission Controversy in Islamic Visual Theory: Alkindi versus Avicenna," in Machamer and Turnbull, *Studies in Perception*; also *Theories of Vision*, chap. 3.

14. The quoted phrase is borrowed, with alterations, from Harold Cherniss, *Aristotle's Criticism of Presocratic Philosophy* (Baltimore, 1935), p. 320. This same objection had been presented in antiquity by Galen, who wrote: "Aristotle was quite correct when he said about the sudden change of bodies thus altered, that it is very nearly instantaneous, and also, with regard to this alteration, that it is the nature of bright air, when altered by colors, to transmit the alteration all the way to the organ of sight. *But Aristotle did not explain how we distinguish the position or size or distance of each perceived object*" (*De placitis Hippocratis et Platonis* 7. 7, in *Opera omnia*, ed. C. G. Kühn, vol. 7 [Leipzig, 1824], p. 638; translation by Philip De Lacy, forthcoming in the *Corpus Graecorum medicorum*).

15. *Ten Treatises*, trans. Meyerhof, p. 32.

16. Under this rubric he includes Plato's theory as well as those of Aristotle and the atomists.

17. The same claim was made by Hunain in the passage quoted above.

18. I must point out that al-Kindi's argument has been reconstructed from brief and fragmentary remarks; I believe, nevertheless, that the reconstruction is secure. See Lindberg, *Theories of Vision*, pp. 22–24, for more detail.

19. See ibid., pp. 27–30.

20. I have chosen not to indicate the refraction of radiation at the front surface of the eye and the interfaces between transparent humors, for fear of implying a level of geometrical precision that many medieval theories of vision did not, in fact, possess. Some medieval authors, such as Alhazen, had an excellent understanding of the qualitative features of refraction, and if it were clear what relative optical densities they assigned to the three humors, we could, without misrepresentation, illustrate their theories of radiation through the eye. However, this would not alter the point of the drawing—namely, that rays from all parts of the visual field mix in all (or virtually all) parts of the eye.

21. The idea that light is weakened when bent by reflection or refraction can be traced back to Aristotle; it was further defended by Alhazen, employing mechanical analogies. See Aristotle, *Meteorologica* 3. 4, 374b28–30; Lindberg, *Theories of Vision*, pp. 75–76. Although in the Latin version of Alhazen's *De aspectibus* the efficacy of perpendicular rays is explained principally in terms of their greater strength, the Arabic version reveals another explanation (which is also obscurely hinted at in the Latin translation), namely, that "there exist certain privileged directions in the lens *as a sensitive body*" (A. I. Sabra, "The Physical and the Mathematical in Ibn al-Haytham's Theory of Light and Vision," forthcoming in vol. 25 of *Boston Studies in the Philosophy of Science*). My sketch of Alhazen's theory of vision has necessarily been highly abbreviated; for additional detail see my "Alhazen's Theory of Vision and Its Reception in the West," *Isis* 58 (1967): 321–41; and my *Theories of Vision*, chap. 4.

22. At the rear surface of the crystalline humor, the rays are refracted away from their point of convergence at the center of the eye and proceed in roughly parallel fashion through the vitreous humor to the optic nerve and eventually to the junction of the two optic nerves, where vision is "completed." On this aspect of Alhazen's theory of vision, see Lindberg, *Theories of Vision*, pp. 80–84.

23. For elaboration of this point, see ibid., chaps. 4 and 8.

24. Only among Galenists and (in the West) Platonists does one find serious attempts to defend an extramission theory after Alhazen, although (as will be seen) there were intromission theories that included an extramission phase.

25. Robert Grosseteste (d. 1253), to whom much credit has traditionally been assigned for the establishment of the Western optical tradition, lived before all of the sources were available (he seems, for example, not to have known Ptolemy's *Optica* or Alhazen's *De aspectibus*) and, therefore, had only a limited influence on the ultimate shape of Western optics. However, Grosseteste is indeed of great importance for stimulating interest in optics.

26. Both ideas could have been borrowed from Alhazen (whose work Albertus knew to a limited degree) and the former from Avicenna and Averroes. Albertus's fullest exposition of visual theory is in his *Summa de creaturis*, in *Opera omnia*, ed. A. Borgnet, vol. 35 (Paris, 1896), pp. 164–228. On Albertus, see Lindberg, *Theories of Vision*, pp. 104–7.

27. These differing loyalties can be explained at least in part, in terms of general philosophical orientation, for Albertus was a firm adherent of

the Aristotelian system, while Roger (like so many Franciscans) had strong Augustinian and Neoplatonic (and, hence, mathematical) leanings. Bacon presented his visual theory in part 5 of the *Opus maius*, available in a modern edition by John H. Bridges, 3 vols. (London, 1900); and a barely acceptable English translation by Robert B. Burke, 2 vols. (Philadelphia, 1928). For a fuller discussion of Bacon's visual theory, see Lindberg, *Theories of Vision*, chap. 6.

28. The term *species* with the connotation of visual form or image was not original with Grosseteste and Bacon, but had been current in the West for centuries. It was clearly defined by Hugh of St. Victor in the twelfth century: "Species is visible form, which includes two things, [namely,] shapes and colors" (quoted by Pierre Michaud-Quantin, *Études sur le vocabulaire philosophique du Moyen Age* [Rome, 1970], p. 114).

29. *Opus maius*, pt. 5.1, dist. 9, chap. 4, ed. Bridges, 2: 71–72; translation reprinted from Edward Grant, ed., *A Source Book in Medieval Science* (Cambridge, Mass., 1974), p. 394.

30. *Opus maius*, pt. 5.1, dist. 7, chaps. 2–3, ed. Bridges, 2:49–52.

31. The perspectivist tradition is perhaps best defined by its adherence to the doctrines of Alhazen. Bacon added several new teachings, but these did not alter the basic character of the system.

32. It must be noted, however, that many Aristotelians attempted to incorporate some of the mathematics of *perspectiva* into their theories, and it is doubtful that in defending the Aristotelian theory of vision they were consciously repudiating that of Alhazen. Perhaps the best example of these syncretistic tendencies is Nicole Oresme, whose work has been examined by Stephen C. McCluskey, Jr., "Nicole Oresme on Light, Color, and the Rainbow: An Edition and Translation, with Introduction and Critical Notes, of Part of Book Three of His *Questiones super quatuor libros meteororum*" (Ph.D. dissertation, University of Wisconsin, 1974), pp. 1–22.

33. Kepler frequently cited the perspectivists and entitled his principal work (published in 1604) *Supplement to Witelo.*

34. In 1583 Felix Platter first clearly stated that the retina, rather than the crystalline humor, is the seat of the visual power. However, even this conclusion (or one very close to it) was anticipated by an anonymous medieval author in a pseudo-Galenic work entitled *De iuvamentis anhelitus*, and the whole question of retinal sensitivity had a long and intricate history prior to the seventeenth century; see Lindberg, *Theories of Vision*, chap. 8.

35. Kepler provided no figure to illustrate his final theory of vision, but the Keplerian theory of the retinal image is adequately represented in fig. 30, from Descartes' *La dioptrique*, in *Oeuvres de Descartes*, ed. Charles Adam and Paul Tannery, vol. 6 (Paris, 1902), p. 125.

36. On Aristotle's theory of light and color, see above, n. 6. For antiquity more generally, see John I. Beare, *Greek Theories of Elementary Cognition from Alcmaeon to Aristotle* (Oxford, 1906).

37. *Avicenna Latinus: Liber de anima seu sextus de naturalibus, I-II-III*, ed. S. Van Riet (Louvain and Leiden, 1972), pp. 170–72. Albertus Magnus probably hit the mark when he interpreted Avicenna's *radius* as

"the issuing forth of *lumen* along a straight line" (*Opera omnia,* ed. Borgnet, 35:184).

38. *Liber de anima,* ed. Van Riet, p. 173.

39. Avicenna's theory did the same, but Alhazen was perhaps more explicit in insisting that light and color together are the direct objects of visual perception. See *Opticae thesaurus Alhazeni arabis libri septem* (Basel, 1572), bk. 2, chap. 2, sec. 15–18, pp. 34–35.

40. Indeed, Alhazen argued that color cannot be perceived unless its form is accompanied by the form of light; see ibid., bk. 1, chap. 7, sec. 39, pp. 22–23.

41. "Physical and Mathematical." However, note that Alhazen also characterized accidental light in terms of the reflecting properties of surfaces; see ibid.

42. Roger Bacon said explicitly that he usually employed *lux* and *lumen* interchangeably; see *De multiplicatione specierum,* pt. I, chap. 1, included with the *Opus maius,* ed. Bridges, 2:409.

43. Averroes, *Epitome of Parva Naturalia,* trans. Harry Blumberg (Cambridge, Mass., 1961), pp. 15–16.

44. See Anneliese Maier, "Das Problem der 'Species sensibiles in medio' und die neue Naturphilosophie des 14. Jahrhunderts," in Maier, *Ausgehendes Mittelalter,* vol. 2 (Rome, 1967), pp. 419–51. On the related subject of the status of light and color (or their species) in a mirror, see Stephen C. McCluskey, "Images, Colors, and the Rainbow in the Fourteenth Century," *British Journal for the History of Science,* forthcoming.

45. *Opera omnia,* ed. Borgnet, 35:205–10.

46. Bacon, *De multiplicatione specierum,* ed. Bridges, 2:507–11.

47. Maier, "Das Problem," pp. 433–44. Ockham is here employing his principle of parsimony—better known as "Ockham's razor."

48. Lejeune, *Euclide et Ptolémée,* p. 38.

49. A. I. Sabra, "Ibn al-Haytham," *Dictionary of Scientific Biography,* 6:191.

50. For a convenient medieval discussion of geometrical optics, see *John Pecham and the Science of Optics: Perspectiva communis,* ed. and trans. David C. Lindberg (Madison, Wis., 1970), from which this illustration is taken.

51. See Albert Lejeune, *Recherches sur la catoptrique grecque* (Brussels, 1957), pp. 152–66.

52. A. C. Crombie, *Robert Grosseteste and the Origins of Experimental Science, 1100–1700* (Oxford, 1953), pp. 219–25. For a translation of the relevant section from Witelo's *Perspectiva,* see Grant, *Source Book,* pp. 424–26.

53. Bruce S. Eastwood, "Grosseteste's 'Quantitative' Law of Refraction," *Journal of the History of Ideas* 28 (1967):403–14; Crombie, Grosseteste, pp. 120–22.

54. An English translation of this proposition from Witelo's *Perspectiva* is given in Grant, *Source Book,* pp. 412–13. For further analysis, see Lindberg, *Pecham and Optics,* pp. 263–65 n. 123.

55. In his *Meteorology* Aristotle adopted the extramission theory of vision, presumably because in this work he was dealing with the mathe-

matics of vision. On Aristotle's theory of the rainbow, see Carl B. Boyer, *The Rainbow: From Myth to Mathematics* (New York, 1959), pp. 41–55.

56. On Grosseteste's theory and other medieval theories of the rainbow, see ibid., pp. 66–142; Crombie, *Grosseteste*, pp. 124–27, 155–62, 196–200, 226–59; Bruce S. Eastwood, "Robert Grosseteste's Theory of the Rainbow," *Archives internationales d'histoire des sciences* 19 (1966): 313–32; David C. Lindberg, "Roger Bacon's Theory of the Rainbow: Progress or Regress?" *Isis* 57 (1966):235–48.

57. A translation of the most important sections of Theodoric's account is found in Grant, *Source Book*, pp. 435–41. See also the works of Boyer and Crombie cited above, and William A. Wallace, O.P., *The Scientific Methodology of Theodoric of Freiberg* (Fribourg, 1959).

58. Copied from a fourteenth-century manuscript: Basel, Öffentliche Bibliothek, MS F.IV.30, fols. 33v–34r. The sun is at *A* and the observer at *C*. The numbered lines beneath the center of the drawing (in the vicinity of the observer) indicate how an observer fixed in one place will see different colors in different raindrops and how, as he moves, he will see different colors in the same raindrop. The path of radiation is shown within only one of the raindrops.

59. Despite the failure of historians to discover a direct link between Theodoric and Descartes, I do not think we can dismiss the possibility that Descartes had access, directly or indirectly, to Theodoric's manuscripts.