Chapter Thirty-one

The Scientific Revolution

Between the publication of Copernicus' theory in 1543 and the death of Gottfried Leibniz in 1716, several hundred Europeans made and advertised a wide array of scientific and mathematical discoveries. The discoveries changed the outlook of a few people immediately, and eventually of much of the world's population. The term, "Scientific Revolution," is often applied to the advances made in western Christendom during the later sixteenth and the seventeenth century.[1] The discoveries themselves prepared the way for the Enlightenment and for the transition from Christendom to modern civilization. Even more important than the advances already made, however, were a growing interest in experimental science and an expectation of further discoveries in the future. By the beginning of the eighteenth century the Bible and the ancient Greek and Roman writers were beginning to lose some of their authority, sharing the stage now with Copernicus, Galileo, Descartes, Newton and other "moderns."

The contributors to the Scientific Revolution were in their day not yet known as "scientists" (a term not coined until the nineteenth century). They might be labeled according to their specialties, as astronomers, chemists, or physicians. More generally, they were "natural philosophers" or "men of science," "science" being understood broadly as knowledge of all sorts, especially non-religious knowledge. Some of the men of science were eccentric and difficult, most of them were contentious with their rivals, and a few of them suffered from one or more serious physical disabilities. Men of science were greatly honored, however, by universities and often were handsomely supported by princes and kings. Printed books or pamphlets carried the ideas and the names of natural philosophers far outside the places where they lived and worked. If a discoverer decided to write in the vernacular, his book was accessible not only to university men but to a great many people who had little more than an elementary education. By the middle of the sixteenth century fluent literacy was much more widespread than it had been a century earlier, thanks both to the invention of the printing press and to Protestantism, which emphasized the reading of the Bible. If a man of science aimed at more educated readers, he wrote in Latin. Although not many copies of his book would be sold to his fellow citizens, it could be read by the educated class from Ireland and Spain to Lithuania and Hungary. Thus did the Scientific Revolution depend both on the excitement of discovery and on the value of intellectual property, or the striving of individuals for academic recognition and acclaim.

In the Ottoman empire universities had not yet been established in the sixteenth century. The first universities in Greece (or anywhere else in the Balkan peninsula) were not founded until the 1820s and 1830s, after Greece had become independent of Ottoman control.[2] In the earlier period many Christian subjects of the sultan are supposed to have sent their children to a *krypho scholio*, a "secret school," in which priests taught reading, writing and Orthodox Christian doctrine but not much else. In Islamic lands the only kind of higher education generally available was to be found in the madrasa, usually built close to a mosque. An even greater obstacle to the Scientific Revolution in the Dar al-Islam was the ban (enforced by the sultans until late in the eighteenth century) on the printing of books in Arabic, Turkish, Persian or any other language written in the Arabic script. As a result, the Scientific Revolution took place almost entirely in western Christendom, and more precisely in Britain and northern Europe.

The Copernican solar system

Long in preparation, Copernicus' *De revolutionibus orbium coelestium* was finally published in 1543, when Copernicus himself was on his death bed. Eventually the book resulted in a great leap forward for science, but immediately its consequences were slight. Thomas Kuhn has made clear how deep was the resistance to the Copernican model of the solar system, most astronomers remaining unconvinced of it until early in the seventeenth century.[3] The geocentric system of Claudius Ptolemy was entrenched both in Christendom and the Dar al-Islam. For almost a millennium and a half it had satisfied the common sense of the general public, and in its complex details it had offered to astronomers a satisfactory explanation of most celestial phenomena.

Copernicus' startling proposal was that the sun and moon did not travel around the earth each day, but that the earth daily completed one rotation on its axis and annually made one orbit around the sun. That the earth was in fact rotating at the blinding speed of a thousand miles per hour, and was at the same time hurrying along on its immense orbit of the sun, was so contrary to common sense that the average person could not regard the Copernican system as anything but an utter absurdity. The earth, it was plain to see, was perfectly stationary while the heavenly bodies were in motion around it. Astronomers found Copernicus' charts and diagrams very helpful, and in its details the *De revolutionibus* was soon acknowledged as more reliable than the *Almagest* of Ptolemy. Sea captains found that celestial navigation manuals based on Copernicus' new system were superior to those long in use. Even astronomers, however, were slow to accept Copernicus' heliocentric system. They treated it as a mathematical model useful for calculations, but not as a physical fact.

Support for the Copernican system came from the meticulous astronomical observations made and recorded by Tycho Brahe and, after Tycho's death in 1601, by Johannes Kepler. These observations were made with the naked eye, but were so accurate and voluminous that they persuaded a growing number of astronomers that Copernicus' system was correct and Ptolemy's was wrong. Kepler concluded that the planetary orbits around the sun were elliptical rather than perfectly circular, and that the planets moved faster when their orbits took them closer to the sun. Stronger support for the Copernican theory came soon thereafter, from Galileo and the telescope. A Dutch lens-crafter's invention of the telescope in 1608 was immediately seized upon by Galileo, who improved the instrument and focused it upon the planets. He was able to see that moons orbited the planet Jupiter, that Saturn was surrounded by rings, and that both planets appeared to travel in orbits around the sun. In 1610-11 Galileo also discovered "spots" on the sun and confirmed that the Milky Way was indeed a huge cluster of stars (since antiquity this had often been proposed and as often denied). In the following decades astronomers, building on the discoveries of Tycho, Kepler and Galileo, refined and revised Copernicus' system.

Europeans derived little practical benefit from Copernicus' theory and later astronomers' validation of it. The "Copernican revolution" is so called because eventually the theory and its confirmation brought with it a profound change in the way in which Europeans looked upon themselves and their relation to the universe. The traditional Ptolemaic system had been anthropocentric as well as geocentric. The earth was the center of the universe, and around the earth circled the moon, the sun, the planets, and - in the farthest sphere - the stars. As Judaeans, Christians and Muslims saw it, God had created all the vast heavens for the benefit of the earth and more specifically of humankind. This comforting picture was spoiled by Copernicus' book. In his system, the sun was fixed at the center of the universe, and the earth - with its human passengers - was the third of six planets that orbited around the sun.

Nevertheless, Copernicus still regarded the universe as finite. The universe had the sun at its center, and at its perimeter was the sphere of the stars. Although the earth was no longer at the very center of things, it was still close to it, and certainly nowhere else in the universe could there be a planet such as ours. With the aid of their telescopes, however, seventeenth-century astronomers displaced our sun from the center of the universe, and described it instead as just one of the countless stars. To the naked eye, the Pleiades constellation appeared to contain seven stars. In 1665 Robert Hooke, using a twelve-foot telescope, found that far beyond the seven readily visible stars were many more (he identified seventy-eight stars in the Pleiades and knew that with a larger telescope he would be able to see many others at still greater distances).[4] The universe, it was beginning to appear, may be limitless, and it was not impossible that as the solar planets make their orbits around the sun, so may other planets be revolving around other stars. In Kuhn's summary, "by 1700 the unique earth, which Copernicus had reduced to but one of six planets, had become little more than a speck of cosmic dust."[5]

Although the earth was at the center of the Ptolemaic universe, it was neither in the *Almagest* nor in Christian dogma the noblest part of the universe. While the earth was known to be a mixture of good and bad, the heavens were supposed to be purely good. This notion too was upset, when Galileo discovered sunspots. His discovery and his interpretation of the sun spots as some kind of disturbance in the sun itself "profoundly questioned a fundamental Aristotelian distinction between the physics of the heavens and that of the earth." In Aristotle's cosmos change, decay, and blemishes were characteristic of the earth, whereas "the sun, the stars, and the planets obeyed quite different physical principles. In their domains there was no change and no imperfection."[6] Galileo's findings brought the heavens down to earth.

Protestants had denounced Copernicus' heliocentric theory as soon as they heard about it. They objected that a stationary sun and a moving earth contradicted the Bible, which in various passages spoke of the earth as standing still and of the sun as rising and setting.[7] The Catholic church did not condemn the Copernican system until 1616, by which time - thanks to the telescope - interest in it was increasing among the general public. In the wake of the "imprisonment" of Galileo, the Catholic church went further, in 1633 prohibiting its members to teach the Copernican system. In several Catholic kingdoms the machinery of the Inquisition was made available to detect and root out those who did not conform.[8] By 1633, however, the Copernican system was accepted in many universities, and even outside the universities a growing number of educated people were persuaded that the "new" model was correct: previously daunted by the mathematical arguments of Tycho and Kepler, the average person could now see with a telescope the evidence to which Galileo had called attention.

Resistance to Copernicanism continued through the seventeenth century, mostly for religious, aesthetic or philosophical reasons. Gradually, however, in most of Christendom philosophers, poets and clergymen yielded to the astronomers. In Kuhn's words, "during the century and a half following Galileo's death in 1642, a belief in the earth-centered universe was gradually transformed from an essential sign of sanity to an index, first, of inflexible conservatism, then of excessive parochialism, and finally of complete fanaticism."[9]

The decline of astrology

While astronomy was becoming the queen of the sciences, astrology began its descent from the domain of natural science, being relegated to the rank of an "occult science." Astrology had been revived in the Renaissance along with the writings of Claudius Ptolemy, who was himself convinced of the stars' predictive role, and reached its height of popularity in the early sixteenth century. Nostradamus (1503-1566) was perhaps its most famous practitioner. Although Protestants were somewhat skeptical of astrology (Luther did not believe in it, but his associate Melanchthon did), both Protestant and Catholic astronomers through the sixteenth century continued to assume that it had some validity. Tycho Brahe, Kepler and Galileo believed that for one reason or another the planets affect the course of events on earth. Even Giovanni Cassini (1625-1712) dabbled in astrology in his earlier years. Pope Urban VIII (1623-44) regularly consulted the notorious Tommaso Campanella on astrological questions.

Astrology was based, however, on the geocentric universe of Aristotle and Ptolemy, and it did not fit well with the Copernican system. By the late seventeenth century the educated class increasingly regarded astrology as superstition rather than science. Astronomers of course found no evidence disproving astrology, but neither did they find anything to support it. The older Cassini therefore completely ignored it, as did Christiaan Huygens and Isaac Newton. Philosophers were more explicit than were astronomers in condemning astrology. In his *Leviathan* (1651) Thomas Hobbes listed horoscopy as a "vain conceit" and as merely one of the "innumerable ways of superstitious divination." Spinoza, in a chapter on prophets and prophecy, dismissed "the Magi, who believed in the follies of astrology," and compared it to the reading of animal entrails.[10] Twenty years later Leibniz expressed a similar opinion. In a letter written in 1697 to Marie de Brinon, tireless opponent of Protestantism,[11] Leibniz included "the foolishness of astrology" as one of several superstitions more widespread in Catholic Europe than in the Protestant north.

Optics, biology, chemistry and geology

Of the various sciences, astronomy made the most spectacular advance in the sixteenth and seventeenth century, but other disciplines also made dramatic progress during this period. While the telescope was opening up new vistas for the astronomer, the microscope revealed what had been too small to be seen by the unaided eye. All of this fell within the science of optics. That science was ultimately in debt to several Arabic texts written in Abbassid times. Ibn Sahl, living in Baghdad ca. 980, wrote about the refraction of light in prisms and mirrors, and his work was incorporated in a lengthy eleventh-century Arabic book, the *Kitāb al-manāzir* ("Book on Direct Vision") written in Cairo by Ibn al-Hasan ibn al-Haytham. In his book Ibn al-Haytham shared the results of his careful study of the properties of lenses (primitive lenses, in glass or translucent stone, had been known since antiquity), of the nature of light, and of the anatomy of the eye. An anonymous Latin translation of Ibn al-Haytham's work had been produced by ca. 1200, and copies of the Latin manuscript may have helped to inspire Europeans - and notably Roger Bacon in England - to experiment with reading stones and lenses. By the end of the thirteenth century clumsy reading glasses had come into occasional use in western Europe.

For the next three hundred years little more was learned about optics. The inertia ended with the printing of the *editio princeps* of Ibn al-Haytham's work at Basle in 1572. The editor of the printed edition titled it *Opticae thesaurus Alhazeni Arabis libri septem* ("The Seven Books of the Arabian Alhazen's Treasury of Optics"). The publication of "Alhazen's Treasury" was soon followed by Zacharius Jensen's invention of the microscope (1590), and Hans Lippershey's invention of the telescope (1608). Both men lived and worked in the Netherlands, Lippershey as a lensmaker. A third important Dutch contributor to the science of optics was Christiaan Huygens (1629-95), whose studies were crucial for the development of the wave theory of light.[12]

Another major advance in optics was the formulation of the "law of refraction," made in the early 1600s and possibly in England by Thomas Harriot (or Herriot), who published nothing about it and is therefore known only by name. The law was re-discovered in the Netherlands in 1621 by Willebrord Snel (Latinized as *Snellius*), a professor of mathematics at the University of Leiden. Snel often spoke about the law but - like Harriot - did not publish his conclusions. Publication finally came with René Descartes' *Discours de la méthode* (1637). Descartes claimed to have discovered the law independently and may indeed have done so, but it is also possible that he had seen notes about Snel's discovery. In any case, the pioneering work on refraction had been centuries earlier by Arabic polymaths.

The microscope revealed organisms too small to be seen by the naked eye. These were drawn, and woodcuts of the drawings were printed, bringing them to the attention of many readers. This was especially the work of Robert Hooke, who from 1662 almost until his death in 1703 was the Curator of Experiments for the Royal Society in London. Hooke was reportedly (no portrait of him survives) small and physically unattractive, but he was a polymath and was regarded by his contemporaries as a genius. He came to wider public attention through the illustrations that he drew for his book, *Micrographia*, published in 1665. Hooke's famous drawing of a flea, which he made for a folio edition of the *Micrographia*, is eighteen inches across. With his microscope Hooke found that the eye of a fly looks, in varying lights, like a surface covered with golden nails, with pyramids, or with cones, and for his readers he drew an illustration of what he had seen.[13] The word "cell," denoting the basic unit of a living organism, first appeared in Hooke's description of cork in his *Micrographia*.

Equally important contributions to an understanding of microscopic life were made in the Netherlands by Anton van Leeuwenhoek (1632-1723), who did not come from a privileged family and did not have a university education. Although van Leeuwenhoek made his living at various businesses in the city of Delft, his avocation was microscopy. He made lenses for himself and improved them sufficiently that he was able to magnify objects more than two hundred times. In 1674 van Leeuwenhoek was the first to see bacteria, and during his long career he also observed, described, and drew species of algae, human and animal sperm, various parasites, and much else. The consequences of these discoveries for biology in general, and especially for microbiology, were enormous.

The science of chemistry was relatively slow to develop from its roots in medieval alchemy. Serious work in chemistry did not begin until discovery of the law of the conservation of mass: the conversion of solids or liquids into gases does not diminish the mass, or weight, of the matter converted. This law was established by experiments done by Mikhail Lomonosov and Antoine Lavoisier in the middle and later decades of the eighteenth century. These chemists, however, were much indebted to work done a century earlier by Robert Boyle and his assistant, Robert Hooke. In 1661, Boyle's *The Sceptical Chymist* attacked the "spagyrists," and their dogma that salt, sulphur and mercury were the "principles" or elements of matter. Although he began as an alchemist, with hopes of transmuting base metals into precious metals, Boyle later helped to distinguish chemistry from alchemy. With the help of Hooke, he articulated what is now known as "Boyle's law": the pressure of a gas is inversely related to its volume. This discovery laid the foundations for the achievements of Lomonosov and Lavoisier.

A comprehensive study of geology did not begin until the eighteenth century,[14] but a tentative study appeared in 1669. This was Nicholas Steno's book, *De solido intra solidum contento dissertationis prodromus*. A literal translation of the title would be, "A prologue to a dissertation on solids contained within solids." What Steno meant by the "solids" contained within other solids are what we would today call "fossils," but the latter word was not yet in use in the seventeenth century. Steno had made a careful study of fossils, traveling extensively to do so, and formulated several important principles of stratigraphy. Most important, perhaps, was the theory that a layer of rock containing fossils of sea creatures must at one time have been under water, even if now that rock layer is far above sea level. Microscopic examination of fossils had earlier convinced Robert Hooke that shell-like fossils found in stone had been imprinted long ago from shell-fish trapped by earthquakes or other natural catastrophes (the popular explanation of fossils was that God or nature occasionally produces stone with imprints that look like living organisms).

Anatomy and physiology

The discovery of infinitesimal forms of life under the microscope eventually led to the germ theory of disease, but this theory was not formulated until long after the careers of Hooke and van Leeuwenhoek. Only in the middle of the nineteenth century did Louis Pasteur show that a variety of infectious diseases are caused by microorganisms that are transferred from one person to another and rapidly reproduce in the recipient. To prevent these infectious diseases, Pasteur insisted, the harmful microorganisms or "germs" must be killed by soap and hot water, by "pasteurization," by vaccines, or by strengthening the body's own ability to fight against the germs. Until advances were made in chemistry, and until the germ theory was accepted, medicine made less progress than did other sciences.

The understanding of human anatomy improved more quickly. Here the foundations were laid in the sixteenth century by Andries van Wesel, Latinized as Andreas Vesalius. Between 1541 and 1543 Vesalius dissected dozens of human cadavers and found that much of the anatomical wisdom of the ancient Greeks, from Aristotle to Galen, was incorrect. He published his discoveries in a wonderfully illustrated seven-volume work, *De humani corporis* *fabrica* (“On the structure of the human body”). Although initially condemned because of its criticism of Galen, who was regarded as an unimpeachable authority, by the middle of the seventeenth century Vesalius’ work was generally recognized as superior to that of the ancient masters.

A very important breakthrough in the science of anatomy was a correct understanding of the heart, lungs, and circulation of the blood. Ibn al-Nafis (1213-1288), a highly respected physician and a prolific writer on medical and anatomical topics, theorized correctly about circulation of the blood from the heart through the lungs and back to the heart. The traditional view, presented by Galen and accepted throughout medieval Christendom and the Dar al-Islam, was that blood passed directly through the septum, via pores so small that they could not be detected, from the right ventricle to the left ventricle of the heart. Ibn al-Nafis’ correct explanation went mostly unnoticed in the lands - Syria and Egypt - where he lived and wrote. Possibly his theory was transmitted to Christendom, either in Arabic or through a Latin translation (not yet found) of one of his works. For example, Michael Servetus vaguely described the circulation of the blood from the right ventricle through the lungs and then back to the left ventricle of the heart (Servetus’ description appears in his *Christianismi restitutio*).

In Europe the effective “discovery” of the blood’s circulatory system can be credited to Matteo Realdo Colombo. Colombo was a professor of anatomy at the University of Padua, which at the time was the pre-eminent center for medical and surgical education. Colombo had studied anatomy with Vesalius, who insisted that there were no pores in the septum through which the blood could pass from the right to the left ventricle of the heart. A fairly detailed description of the circulation of the blood was published by Colombo in his *De re anatomica libri xv* (1559), in which he claims it as his own discovery. It was not, strictly speaking, Colombo’s own discovery, but what is important is that Colombo celebrated the correct description as a discovery, or as an improvement on the knowledge passed down from antiquity. Ibn al-Nafis had also made significant improvements on his own, and called attention to them in his commentary on Avicenna’s *Canon*. But in the Dar al-Islam such improvements (or advancements) got little attention.

In Christendom, thanks in large part to the printing press, they did. Although Colombo’s work was ignored by most physicians, it impressed the best and the brightest. Most importantly, it came to the attention of William Harvey, who as a young man had studied anatomy at Padua. Harvey eventually wrote what became the definitive work on the subject: his *Exercitatio anatomica de motu cordis et sanguinis in animalibus*, published in 1628. The authority of Galen was still so great that for twenty years Harvey’s presentation was dismissed by most practicing physicians in Europe. But as Harvey’s book came to the attention of professors in medical schools, its conclusions came to be accepted by the professors and their students. The result was that by the end of the seventeenth century the discovery and Harvey himself were cause for celebration. The ancient Greek wisdom was wrong, and had now been corrected.

Ancient views about reproduction were also eventually undone by discoveries made during the Scientific Revolution. One ancient view, favored by Aristotle, was that an embryo came from a combination of male semen with female uterine blood. Galen, contrarily, held that females released seed during intercourse, just as males did, and that from the combination of these male and female seeds a fetus was formed.[15] It was William Harvey, again, who pioneered the theory that female mammals ovulate: like birds, female mammals produce eggs, which when fertilized by male semen became embryos. No such mammalian eggs had yet been seen, and Harvey's theory of ovulation encountered resistance until it was confirmed in the early nineteenth century. It launched, however, a sustained interest in human and animal reproduction.[16] In the Netherlands the youthful Reinier de Graaf in 1672 discovered the "Graafian follicles" in what - thanks in large part to de Graaf - are now called the ovaries, and he speculated that ova were there produced. Soon after de Graaf's untimely death van Leeuwenhoek discovered countless spermatozoa (*animalculi*, as he called them) in the semen of men, of other male mammals, and of reptiles.

The new science: Bacon and Descartes

Equally important as the seventeenth-century discoveries were analyses of the way in which discoveries are made, or the way in which knowledge grows. Francis Bacon's *On the Proficience and Advancement of Learning, Divine and Human*, dedicated to King James I and published in 1605, made a modest move in this direction. Much of Bacon's effort here - in a text dotted with Latin quotations from the Bible and from classical authors - was spent in showing that the Bible and the ancient Romans were not so adamant in opposing philosophy as some people imagined. More important than his *Advancement of Learning* was Bacon's *Novum organum*, published in 1620. The old *Organum* was Aristotle's, and Bacon intended his *Novum organum* to promote a "new system of logic" that the ancients had never tried.

Bacon's *Novum organum* argued that the unaided mind can achieve no more than can our unaided muscles: machines - instruments, such as the microscope and telescope - are required if we want to achieve something substantial. Newton noted that although Aristotle did some experiments, it was invariably to prove something he had already concluded, rather than to discover the truth. In order to reach the truth, Bacon urged, one must rely on inductive rather than on syllogistic or "anticipatory" reasoning: most of what we claim to know are broad generalizations, each of which is based on a few random observations.

What is needed, he proposed, was a laborious and systematic progression from a question to an answer.

> There are and can be only two ways of searching into and discovering truth. The one flies from the senses and particulars to the most general axioms, and from these principles, the truth of which it takes for settled and immovable, proceeds to judgment and to the discovery of middle axioms. And this way is now in fashion. The other derives axioms from the senses and particulars, rising by a gradual and unbroken ascent, so that it arrives at the most general axioms last of all. This is the true way, but as yet untried.[17]

One of Bacon's most famous sentences is, "If a man will begin with certainties he shall end in doubts; but if he will be content to begin with doubts he shall end in certainties." As for the syllogistic logic inherited from Aristotle and the Schoolmen, Bacon complained that "the logic now in use serves rather to fix and give stability to the errors which have their foundations in commonly received notions than to help the search after truth. So it does more harm than good."[18]

René Descartes (1596-1650) was a younger contemporary of Francis Bacon. As a child, Descartes was frail and frequently sick, but he came from minor nobility and was given special treatment when - at the age of ten - he was sent to a Jesuit academy at La Flèche, a small city in northwestern France. He graduated from the University of Poitiers with a degree in canon law, but was more interested in "natural philosophy" (science and mathematics) than in law. What philosophy he had studied seemed to him, as it had to Bacon, inadequate for an age in which the frontiers of knowledge were obviously expanding. The Jesuits at La Flèche had depended heavily on Aristotle, as did - to a lesser extent - Descartes' professors at Poitiers. Descartes turned his back on scholastic philosophy, with its emphasis on logic. He also was frustrated - as had been Bacon already when writing his *Advancement of Learning* - that the widespread dependence on "final causes" was hampering a real understanding of the natural world. Statements such as, "A bird has feathers in order to keep it warm," or "We have eyelashes in order to protect our eyes," give only an illusion of explaining facts.[19] Descartes aimed at starting with a clean slate, and constructing a natural science one fact at a time.

As were other natural philosophers, Descartes was a polymath. His contributions to optics have already been noted. As a mathematician he was at least a pioneer if not the inventor of analytic geometry. His most ambitious work, published at Leiden in 1637, was his *Discours de la méthode pour bien conduire sa raison et chercher la verité dans les sciences* ("Discourse on the method of proper reasoning and of finding the truth in the sciences"). Again like Bacon, Descartes insisted that all received axioms be tested before being accepted. One of his mottos was, *de omnibus est dubitandum* ("we must doubt everything"). Descartes spent most of his adult life in the Netherlands, corresponding with many other scholars and also with royalty throughout western Christendom. He died in Sweden in 1650, shortly after accepting a post in the court of Queen Christina.

By the 1660s the "new science," based on experiment and empirical evidence, was being widely hailed. Natural philosophers were encouraged to formulate a testable hypothesis and then to verify or to falsify it by experiment and observation. A famous achievement of the new science was the exploration and explanation of air pressure and of the vacuum. This research was made possible by an air pump invented at Magdeburg ca. 1650 by Otto von Guericke, and further developed in London by Robert Boyle and Robert Hooke (the pump's piston sucked air out of a glass "receiver" and so created a vacuum). Demonstrations of the pump were made before many groups of distinguished guests.[20]

Newton and Leibniz

At the close of the seventeenth century two giants in the field of mathematics - Gottfried Leibniz and Isaac Newton - dominated the intellectual landscape of Europe and Britain. Both men were devoted to the mind. Neither had a conventional childhood. Leibniz's father - a professor of philosophy at the University of Leipzig - died when Gottfried was six years old, and Newton's father died before Isaac was born. Like Spinoza, neither Newton nor Leibniz married, perhaps because they had little sexual motivation and perhaps because they sensed that marriage or similar attachments would divert them from their mathematical interests. Because each man was intensely proud of his reputation, Leibniz and Newton were bitter rivals. Both were men of some political consequence. Leibniz spent much of his life at Hanover, where he was counselor to Sophia, wife of the Elector and ruler of Braunschweig (in English, Brunswick)-Lüneberg. Late in her long life Sophia became heiress to the throne of the United Kingdom (she was a cousin of William III), although she died before taking the throne, which was therefore passed on to her son, George. As Sophia's advisor, Leibniz was involved in the diplomatic negotiations that transferred the British throne to the House of Hanover. Isaac Newton was less involved in court politics, but in the 1680s he served briefly as a member of the English parliament. There he strove to keep James II from returning the universities - Cambridge and Oxford - to the Catholic church.

Newton (1643-1727) was born in the village of Woolsthorpe-by-Colsterworth, a hundred miles north of London. He was educated at Cambridge University and at the age of 26 was appointed the university's Lucasian professor of mathematics, having in the meanwhile made important discoveries in optics. Fascinated by light and color, Newton used prisms, as others had before, and with inventive experiments he showed that white light - light from the sun - could be refracted into the full spectrum of colors. Earlier students of optics had supposed that prisms *added* colors to the white light. These experiments were done in 1665-6, when Newton was 22 years old. He built on the work of Thomas Harriot, Willebrord Snel and René Descartes (Descartes' *Discours de la méthode* had been published six years before Newton was born).

It was in mathematics and physics, however, that Newton made his greatest contributions. Working independently, Newton and Leibniz at almost the same time invented calculus. Although they were men of genius, they were also beneficiaries of studies that had begun with Archimedes and that were advanced in the 1640s by Pierre de Fermat and Blaise Pascal. Newton seems to have arrived at an understanding of calculus, and to have made use of it, already in the 1660s, but Leibniz was the first to publish his method: Leibniz's *Nova methodus pro maximis et minimis* was published in 1684. In the calculus controversy Newton and Leibniz each accused the other of plagiarism.[21]

The new mathematics allowed Newton to formulate his revolutionary laws of inertia and motion. These appeared in his magnum opus, *Philosophiae naturalis principia mathematica* (1687). In the first and second volumes, subtitled *De motu corporum* ("On the movement of masses") Newton set forth his three laws of motion and his general theory of gravitation, explaining in mathematical terms the inertia and movement of mass. The third volume of *Principia mathematica* was subtitled *De systemate mundi* ("On the world system"), and here Newton explained the movement and orbits of the planets. A century earlier Johannes Kepler had shown that the planets' orbits are elliptical, and that the speed with which they travel their orbits depends on their distance from the sun. Newton showed that the planetary orbits and the planets' varying speeds were accounted for by his theory of gravitation.

Most educated Christians had by the 1680s accepted the Copernican system, and many of them had regarded the annual revolution of the earth around the sun, and the earth's daily rotation on its axis, as evidence of God's continuing grace and power. Newton's laws of inertia and motion supplied a physical explanation for both the revolution and the rotation. During the eighteenth century Newtonian physics encouraged the deists in their conception of "the philosophers' God": God created the universe, but since that act of creation the universe - like a finely made pocket watch - has run according to the laws of nature, and God has not intervened.

Newton himself, however, never drew that deist conclusion and continued to believe in the God of the scriptural religions.[22] Newton and Leibniz were both keenly interested in theology. Both were Christians, although their beliefs were far from those of most Christians. Leibniz was raised as a Lutheran and remained a Lutheran and a trinitarian. He was more suspicious of Reformed than of Catholic Christianity: his philosophy allowed a place for mysteries, and so for the Eucharist, which had been devalued in the Reformed tradition. Newton, on the other hand, nominally Anglican, was an Arian or even a Socinian rather than a trinitarian.[23] In the last fifteen years of his life he became much interested in the prophecies of Daniel and of the Book of Revelation, and in the temple of Solomon, which he supposed had been exactly built for worship of "the One Supreme God."[24]

Ideas of history and intimations of progress in western Europe

By the end of the seventeenth century western Europe was not far removed from modern civilization. In what had recently been Catholic Christendom millions of people - most of them Protestants, but also some Judaeans and Catholics - were aware that they no longer believed many things that their ancestors had believed. The word "superstition" was often used by Protestants for belief in the power of relics, rosaries, holy water and other things that for a long time had been revered and unquestioned by most of the laity in the Church.

As the Scientific Revolution advanced, western Europeans began to look at their past as divided into an ancient, a medieval, and a new - or modern - period. This periodizing had been in the air since Petrarch but its first formal appearance was in the years 1685-1696, thanks to Christoph Cellarius, a Lutheran professor of the Greek and Latin classics first at Weimar and then at Halle. In his three-volume universal history Cellarius presented both "ancient" and "new" times in a favorable light ("new times" for Cellarius were the sixteenth and seventeenth centuries) . In his second volume Cellarius described the *medium aevum*, the "age between" antiquity and modernity. To Cellarius, as to many of his contemporaries, this "middle age" seemed to have been a period of barbarism and superstition.[25] Although most European scholars were agreed that the "medieval" period was a trough, they were divided on the relative merits of the "ancient" and the "modern" age. Most of them still assumed that antiquity - with Homer, Vergil, Tacitus and above all Aristotle - was the more admirable. A growing number, however, now took the brash position that the "natural philosophers" of modernity - from Copernicus to Leibniz and Newton - surpassed the ancients. The debate, known in France as the "querelle des Anciens et des Modernes," was satirized by Jonathan Swift and in England came to be called "the Battle of the Books." We may generalize that by the late seventeenth century many people in western Christendom were pleased to be living in what they regarded as "a new age."

Academies of science, and their royal support

Institutions devoted to scientific endeavors were first established in the seventeenth century. These were modeled on earlier humanistic "academies," such as the Accademia Platonica created at Florence by Cosimo de' Medici. The first of the scientific academies was set up at Rome in 1603 by an Italian nobleman, Federico Cesi, who was himself a natural philosopher. Cesi called his foundation the Accademia dei Lincei (“Academy of the lynx”): as the lynx was reputed to have remarkably acute vision, so Cesi hoped that the men invited to membership in his Accademia dei Lincei would observe in nature what had hitherto gone unnoticed. An early member of the Accademia, and then its great luminary, was Galileo. The Accademia had an uneasy relationship with the popes, who were the temporal as well as the spiritual rulers of Rome, and for its financial support it depended entirely upon Cesi. When he died in 1630 the Accademia was disbanded (the present-day Accademia dei Lincei dates from the nineteenth century).

In 1652 four German physicians established an *Academia naturae curiosorum* (“Academy of those who investigate nature”) in the small city of Schweinfurt. Although meant especially to enlarge an understanding of the human body and to improve the art of healing, it also welcomed men of other sciences. The little academy received the blessing of Ferdinand III, Holy Roman Emperor, and received more tangible benefits from his son and successor, Leopold I. It was more a scholarly association than a physical institution, having no library and no permanent headquarters.

In England the Royal Society for the Improvement of Natural Knowledge was established in 1660. Two years later it was given its royal charter by King Charles II, recently returned to England after his flight. The initiative for the institution, which came to be known simply as “the Royal Society,” came from the sizeable company of natural philosophers in London and in the university cities of Oxford and Cambridge. Robert Boyle and Robert Hooke were members of the original Royal Society, as was the architect Christopher Wren. As its name indicates, the project of the Royal Society was to promote “natural knowledge” or “experimental philosophy,” rather than the traditional Aristotelian philosophy.

In the preface to his *Micrographia*, published five years after the foundation of the Royal Society, Robert Hooke looked forward to new discoveries while introducing his own work and the marvelous things he had seen under the microscope:

> And this was undertaken in prosecution of the Design which the *ROYAL SOCIETY* has propos'd to it self. For the Members of the Assembly having before their eyes so many *fatal* Instances of the errors and falshoods, in which the greatest part of mankind has so long wandred, because they rely'd upon the strength of humane Reason alone, have begun anew to correct all *Hypotheses* by sense, as Seamen do their *dead Reckonings* by *Celestial Observations*.

In that same year (1665) the society began publishing the work of its members in *Philosophical Transactions*. At the end of the seventeenth century the Royal Society included among its members Isaac Newton and Edmond Halley, the latter renowned as an astronomer and suspected of being an atheist.[26]

French men of science soon had an institution to match that of the English. In 1666 Jean-Baptiste Colbert, whom King Louis XIV had appointed his minister of finance, established the
Académie Royale des Sciences. Although most of its several dozen members were French,

invitations were also given to prominent natural philosophers - Edmond Halley being one of them - in other states. Christiaan Huygens, from the Netherlands, was an early member. The Bourbon dynasty continued to support the Académie generously, but for that very reason it was loathed by radicals in the French Revolution and in 1793 was temporarily abolished (its leading member, Lavoisier, was hauled to the guillotine in 1794).

Another royal academy of science was organized in 1701, when Frederick III of Brandenburg saw to the establishment of the Königlich preussische Sozietät der Wissenschaften ("Royal Prussian Society of Sciences"). Preeminent among its first members was Gottfried Leibniz, the most distinguished philosopher of his day. Other northern European kingdoms eventually followed suit. In Russia, Peter the Great in 1724 founded the St. Petersburg Academy of Sciences, again with Leibniz's encouragement. Naturalist Carolus Linnaeus was the moving force behind the Royal Swedish Academy of Sciences, set up in 1739, and three years later King Christian VI of Denmark established the Royal Danish Academy of Science and Letters, for the study of both the natural sciences and fields such as history and literature.

Indifference to the Scientific Revolution in the Dar al-Islam

As indicated at the beginning of this chapter, the Scientific Revolution took place mostly in Britain and northern Europe. In southern Europe the creation of academies of science was generally much slower than it was in the north. In Portugal Queen Maria I and King Pedro III founded the Academia das Ciências de Lisboa (Sciences Academy of Lisbon) in 1779. Royal academies of science were not established in Austria and Spain until 1847.

While Catholic Christendom was merely slow to embrace scientific discovery, the Ottoman empire and the Dar al-Islam actively resisted it. Until 1846 the Ottoman empire had no university, to say nothing of a royal academy of science.[27] In the seventeenth and eighteenth centuries the only education accessible for Muslims was what the madrasas provided.

The brilliance of Arabic civilization from the early ninth century to the middle of the thirteenth is finally receiving the attention that it deserves. A recent book pointed out that Arabic astronomers of the Abbasid period helped to pave the way for Copernicus' eventual breakthrough.[28] In the history of early modernity, however, the Dar al-Islam played a very different role: Copernicus lived and worked in the intellectual excitement of sixteenth-century Poland, and his breakthrough created a commotion in western Christendom. For a very long time, in contrast, it attracted little interest in the Dar al-Islam. An early exception was Taqī al-Dīn, who was the chief astronomer (and astrologist) for Sultan Murad III. On al-Dīn's initiative an observatory was built at Istanbul, in the expectation that al-Dīn and his colleagues would rival what Tycho Brahe was doing in Denmark. The Istanbul observatory was finished in 1577, but three years later it was destroyed at the behest of the Chief Mufti. Bernard Lewis remarked that "[t]his observatory had many predecessors in the lands of Islam. It had no successors until the age of modernization."[29]

No mention of Copernicanism can be found in Arabic (or Turkish) texts until the early 1660s. Notice of the new system in Arabic first came by way of a mariner's manual compiled by Noel Durret. Durret's *Novae motuum caelestium ephemerides richelinanae* (1641) was translated from Latin into Arabic by Tezkireci Köse Ibrāhīm Efendi.[30] Included in Durret's work and in Tezkireci's translation were drawings of the Ptolemaic and Copernican universes, and a discussion of both. Evidently few copies were made of Tezkireci's Arabic manuscript, for the only exemplar was found in the early 1990s, in an Ottoman archive at Istanbul (presumably the manuscript had lain in the archive for three hundred years). The Arabic translation, however, was soon followed by a translation into Turkish, of which several hand-copies were made by seventeenth-century scribes (printing of any text written with the Arabic alphabet was not permitted until the late eighteenth century). The empire's chief astronomer, when presented with a copy, told Tezkireci that the Copernican system was just another vanity of Christian Europe, but eventually he admitted the value of Durret's almanac, especially for celestial navigation.[31] Despite that concession, serious interest in the Copernican system was not awakened in the Ottoman empire until near the end of the nineteenth century, when "the Young Turks" began to call for more science and less religion (the madrasas in Turkey were closed in 1924).

Because it was the crucible for the Scientific Revolution, western Europe soon entered the Enlightenment. In that period Christianity - as we shall see in Chapters 33 and 34 - was drastically trimmed, and Christendom began its evolution into modern civilization. By the end of the eighteenth century, with the Haskalah, the secularization of Judaism in western Europe had begun. Islam experienced little or none of this. Thanks to the intellectual inertia of the Ottoman empire, throughout the Scientific Revolution and in the generations that followed Islam remained essentially beyond criticism.

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1. The term, "Scientific Revolution," came widely into use with two books - one written by A. Rupert Hall and the other by John Desmond ("Sage") Bernal - published in 1954. Bernal's *The Scientific and Industrial Revolutions* was the second volume of his four-volume *Science in History*, published by M.I.T. Press in Cambridge, Mass. See also Alfred Rupert Hall, *The Scientific Revolution 1500-1800: The Formation of the Modern Scientific Attitude*, 2nd edition (Boston: Beacon, 1966). Recently Steven Shapin has published an excellent survey and interpretation of the so-called Scientific Revolution. See Shapin 1996, to which the present chapter owes much.

2. The Othonian University established in Athens in 1837 by King Otto is now the National and Kapodistrian University of Athens. Still earlier was the Ionian University, founded on the island of Ithaca in 1821, and transferred to Korfu in 1824.

3. Kuhn 1966, especially pp. 185 ff.

4. Shapin 1996, p. 27. With his smaller telescope, Galileo had seen 36 stars in the Pleiades.

5. Kuhn 1966, p. 232.

6. Shapin 1996, p. 17.

7. Psalm 93:1-2 praises Adonai with the words, “The earth is established immovably, your throne is established from of old” (OSB). The first line of the phrase appears also at Psalm 96:10, and I Chron 16:30. At 104:5 the psalmist’s wording is slightly different: “You fixed the earth on its foundation so that it will never be moved” (OSB).

8. For the Protestant and Catholic response to Copernicus’ ideas see Kuhn 1966, pp. 191-200.

9. Kuhn 1966, p. 227.

10. For Hobbes’ statements see *Leviathan*, Chapter XII, a chapter entitled, “Of Religion.” For Spinoza’s condemnation see *Tractatus theologico-politicus* 2:38 (R. H. M. Elwes’ 1883 translation from the Latin).

11. Marie de Brinon was the secretary to Bishop Jacques-Bénigne Bossuet (who in turn was the spiritual advisor to Louis XIV). On Leibniz’s correspondence with de Brinon see Stewart 2006, pp. 263-4.

12. On Huygens see the dissertation by Fokko Jan Dijksterhuis, *Lenses and Waves: Christiaan Huygens and the Mathematical Science of Optics in the Seventeenth Century* (Dordrecht: Kluwer, 2004).

13. See Shapin 1996, pp. 143-47, with his figures 27-29, for discussion of the microscopic discoveries and reproduction of some of the seventeenth-century illustrations.

14. James Hutton (1726-97) has often been called the father of geology.

15. Aristotle, *Generation of Animals* 1:19-20. The original Greek text of Galen’s *Peri spermatos* is now lost, but translations were made from it into Syriac and Arabic, and from these Semitic texts a Latin translation was made in the 14th century.

16. On which see Smith 2006.

17. *Novum organum* 1.19 (translation of Spedding, Ellis and Heath).

18. *Novum organum* 1.12.

19. Voltaire parodied the use of final clauses: we have noses in order to keep our eyeglasses in place.

20. See Shapin 1996, p. 96: “The Royal Society vigorously advertised its experimental program throughout Europe, and experiments with the air pump were repeatedly pointed to as a paradigm of experimental philosophy... Many histories of experiment in natural science plausibly tell origin stories tracing back to Boyle’s air pump.”

21. On this see A. Rupert Hall, *Philosophers at War: The Quarrel between Newton and Leibniz* (Cambridge: Cambridge University Press, 1980).

22. See Shapin 1996, pp. 152-53. Newton's universe had a need for God's intervention. According to Newton's calculations, the solar system had a tendency to collapse into itself, and that it did not do so was evidence of God's intervention, either directly or indirectly through comets or other natural objects.

23. According to Snobelen 2005, p. 242, "Newton's theology and religious life reveal a host of parallels with Socinianism."

24. In his last fifteen years Newton labored on his *A Chronology of the Ancient Kingdoms Amended*, which was published posthumously. In this book, a farrago of Greek myth and Biblical "history," Newton attempted to lower the chronologies of Mesopotamia and Egypt, so as to make them follow rather than precede the kingdoms of Israel and Judah. The purpose of all this "amending" of chronologies was to make the Jerusalem temple the earliest of all temples. Newton dated Solomon's construction of the temple to 1015 BC, and made it contemporary with the reign of Minos on Crete. Chapter 5 of the *Chronology* is devoted entirely to the precise dimensions of the temple and of each of its architectural elements. Although apparently not a freemason, Newton shared with the early freemasons a deep interest in the occult, in "ancient wisdom," and in Solomon's temple.

25. Cellarius (Keller) published his *Historia antiqua* in 1685, and followed it with *Historia medii aevi* in 1688 and *Historia nova* in 1696. His *medium aevum* began with Constantine and ended at 1500. On Cellarius' predecessors in periodizing history see Arnold 2008, pp. 8 ff. At p. 9 Arnold writes, "The important thing to note here is that from the moments of its inception, 'medieval' has been a term of denigration.... Both the ancient 'then' and the contemporary 'now' were thrown into stark relief by the darkness in between: a darkness of ignorance, decay, chaos, confusion, anarchy and unreason."

26. Halley proposed natural explanations for what were believed to have been miraculous Acts of God. After making an intensive study of comets, Halley proposed that "Noah's Flood" was caused by a comet that collided with the earth at the Caspian Sea, spilling out its waters onto surrounding lands.

27. On the gradual introduction of European science to the Ottoman empire see Ekmeleddin Ihsanoglu, *Science, Technology, and Learning in the Ottoman Empire: Western Influence, Local Institutions, and the Transfer of Learning* (Burlington, VT: Ashgate/Variorum 2004).

28. George Saliba, *A History of Arabic Astronomy: Planetary Theories during the Golden Age of Islam* (New York University, 1994). In his most recent book Saliba enlarges upon the thesis of Arabic stimuli for the intellectual breakthroughs in Europe: see George Saliba, *Islamic Science and the Making of the European Renaissance* (Cambridge, Mass.: MIT Press, 2007). His subject in this book, however, is not Islamic science but Arabic science.

29. Lewis 2002, pp. 80-81.

30. In the Dar al-Islam the compilation of an ever more accurate *zij* (a table of celestial positions of the sun, moon and planets) was a common task for astronomers. Several hundred of these tables are known. The *zij* of Ulugh Beg in 1437 was the best of these and the last important

one. It was translated into Latin and published by Thomas Hyde in 1665.

31. Avner Ben-Zaken, "The Heavens of the Sky and the Heavens of the Heart: the Ottoman Cultural Context for the Introduction of post-Copernican Astronomy," *British Journal for the History of Science* 37 (2004), pp. 1-28.