Part Three

New Cultural and Political Horizons

During the late seventeenth century and the eighteenth century, Europe entered a period of remarkable intellectual and political ferment. Rejecting the weight of tradition, men and women of science developed the scientific method, a means of understanding based on systematic observation of natural phenomena and experimentation regarding causes and effects. Their successors, the philosophes—the thinkers and writers of the Enlightenment—believed their role was to bring progress to the world through the application of reason to their reflections on the nature of mankind. Influenced by growing religious skepticism and increased knowledge of the New World brought through overseas trade and the establishment of European empires, and drawing on expanding literacy, the philosophes espoused views of nature, mankind, society, and government that challenged some of the fundamental tenets most Europeans shared.

During this exciting period, Europe also entered a remarkable time of economic and social change. Increased agricultural productivity supported a larger population that, in turn, raised the demand for food and permitted the development of large-scale manufacturing in and around northern English towns.

Changes also came in the realm of political life. The public political sphere was transformed by the emergence of newspapers and learned associations, which facilitated political interest and discussion. Reform-minded people began to denounce unwarranted privilege and "despotism," and they celebrated the British model of constitutional monarchy and the successful rebellion of the American colonists against British rule. In a time of economic and social change, new cultural and political innovations began to transform Europe.

CHAPTER 8

THE NEW PHILOSOPHY OF SCIENCE

In 1633, ecclesiastical authorities summoned the astronomer and physicist Galileo Galilei (1564–1642) to Rome to face the Inquisition. The stakes were high. In the first year of the new century, the Italian Giordano Bruno (1548–1600), a Dominican friar accused of heresy who loudly proclaimed the virtues of scientific investigation, had been burned along with his books in Rome. Many Church fathers vehemently objected to Galileo's work on physics, for he, like Bruno, espoused an atomistic theory of matter that seemed to challenge the Catholic Church's view that during communion bread and wine become the body and blood of Christ. The Church also opposed Galileo's contention that the earth revolves around the sun. The papacy's political situation forced the Church's hand. Protestant armies had recaptured some of the lands in which the Catholic Reformation had appeared victorious. The papacy, its influence weakened by the Protestant Reformation and eclipsed by powerful dynastic rulers, could ill afford another defeat.

Pope Urban VIII, who before his elevation to the pontificate had been Galileo's friend, accused the astronomer only of supporting the views of the Polish scientist Copernicus, not of heresy. This would save Galileo from death but might also put the pope in a bad light for protecting the scientist. Although Galileo agreed to renounce these "errors" as heresies in order to avoid a death sentence, in 1633 he was still sentenced to a lifetime of house arrest. When guards returned him to his house, however, he cast a glance to the heavens and proclaimed of the earth, "See, it's still moving!"

The origins of modern science date to the seventeenth century, a period so marked by innovative thinking that it has been called the "century of genius." In several different corners of Europe, a few people struggled to understand the workings of the cosmos in a new way. Their own observations of the skies seemed to contradict explanations of the universe that had originated with Aristotle in the fourth century B.C. and, having acquired the authority of the Church, had been passed down for centuries. Breaking free of the bonds of tradition, these seventeenth-century thinkers developed the scientific method, a means of understanding based on systematic observation of natural phenomena and experimentation regarding causes and effects. But what we now know as the Scientific Revolution owed its impact less to new technology and inventions than to new ways of thinking about the universe.

Changing Views of the Universe

The writings of the Greek philosopher Aristotle (384–322 B.C.) dominated European science for centuries. Then, in the sixteenth century, the Polish astronomer Copernicus observed the heavens and concluded that ancient and medieval science could not explain what he saw with his own eyes. Later in the century, his successors—above all, Galileo—made systematic mathematical calculations to explain celestial motion. In doing so, they created scientific methodology, which would also be applied to reach an understanding of the workings of the human body.

Ancient and Medieval Science

Aristotle believed that the earth was located at or near the center of the universe. He envisioned a hierarchical order of the cosmos comprised of a series of spheres that became progressively purer. Aristotle also believed that terrestrial bodies naturally moved toward the earth, the center of the universe, unless they were propelled in another direction. In this view, impetus imparted motion through contact with an object; when the contact ceased, the object simply stopped moving or fell back to earth. The natural tendency of all matter, then, was toward rest, regarded as a nobler state than motion. Because all motion had to be explained, a "mover" therefore had to be found for every motion.

In the second century A.D., the Greek astronomer Claudius Ptolemy (c. 85–165) published a massive work that became known as *Almagest* (from the Arabic for "greatest"), which summarized the conclusions of Greek astronomers and presented his own theories and observations. He described instruments such as the quadrant, invented by the Arabs, with which he tried to measure the orbits (which he believed to be spherical) of the sun, moon, and planets in the sky. Ptolemy accepted Aristotle's contentions, asserting that the earth was encased by a series of clear spheres—about eighty—revolving around it. The most distant sphere contained the farthest stars, which he believed were fixed points of light. Within those spheres, the moon was closest to the earth; next came the planets Mars, Venus, Jupiter, and Saturn. With minor variations, medieval thinkers still held Ptolemy's views.

Within the context of Christian theology, people of learning in the Middle Ages believed that scientific inquiry should serve theological ends through the study of nature to explain the mysterious ways of God. Church savants never raised the possibility that mankind could, with understanding, alter or master nature.

Aristotle's belief that the heavens and earth displayed two different kinds of motion—one toward the center of the earth, which seemed the natural state, but also an unnatural violent motion away from it—nicely fit the medieval Church's view that the universe consisted of good and evil. The earth, standing at the center, was heavy, corrupted not only by its weight but also by original sin and earthly misdeeds. Angels therefore were placed far off in a weightless existence in Heaven. The goal of human beings was to achieve the lightness of Heaven, God's domain, on the exterior edge of the universe.

The writings of the medieval poet Dante (1265–1321) reflected the prevailing influence of Aristotle's physics and Ptolemy's astronomy. Dante held that the universe comprised ten spheres surrounding the spherical, motionless earth. In his *Inferno,* Dante and the Roman poet Virgil travel to the core of the earth, then climb out to the other side, the Southern Hemisphere, where they find Purgatory. Hell lay at the earth's center, with Heaven in the distant tenth sphere. Dante and his contemporaries believed that the earth consisted of four elements: earth, water, air, and fire, the first two of which had a natural tendency to fall toward the center of the stationary earth.

Medieval European scholars seemed little interested in astronomy. Yet, to be sure, some medieval thinkers took significant steps toward modern science by embracing the study of natural phenomena and revering the

Virgil, Cicero, and the Three Giants in the Lost Circle, from Dante's *Devine Comedy (The Inferno),* 1313.

scholars who studied such problems. Medieval scientists made lasting contributions in such fields as optics—inventing eyeglasses—and biology. They classified objects for study and espoused experimentation based on scientific procedures and the use of mathematics to verify theories. But even the contributions of the most brilliant medieval thinkers remained only in the realm of theory.

As the Renaissance drew on the discovery of classical prose, poetry, art, and architecture, Italian scholars of the period also turned to classical Greek scientific texts that had been recovered, edited, and printed. The Arabs had come into contact with classical learning centuries earlier, when they conquered the eastern reaches of the Byzantine Empire. Arab scholars, who also made significant original contributions in astronomy, mathematics, and medicine, preserved many ancient Greek and Roman texts, translating them into Arabic. Some of the manuscripts brought by Greek scholars to the West from Constantinople after its conquest by the Turks in 1453 suggested that mathematics could be applied in the quest for knowledge about the universe. Arab scholars had raised troubling questions challenging age-old views of the earth as they observed and even began to measure the heavenly phenomena they beheld. In this way, the texts of Ptolemy became subjects of renewed interest and study.

Ptolemy's view of the cosmos reflected the domination of Aristotle's theory of motion. Yet there had earlier been at least one dissenting voice. Archimedes of Syracuse (c. 287–212 B.C.) had challenged Aristotle's contention that rest was a natural state for all objects and that only the presence of an "active mover" could generate motion. This view was picked up again in the fourteenth century by thinkers at Paris and Oxford Universities. They observed that falling bodies move at an accelerating speed and that the accompanying presence of a "mover" simply could not be observed. A few scholars also rejected Aristotle's explanation that air itself served as a natural propellant. They observed that an arrow shot from a bow clearly was not continually propelled by air or anything else, but sooner or later simply fell to earth. The gradual development of a theory of motion, based on an understanding of the role of the mass of the moving object, along with the advances in the field of mathematics itself, provided the basis for new discoveries in astronomy and mechanics.

Copernicus Challenges the Aristotelian View of the Universe

The revolution in scientific thinking moved forward because of a cleric who kept his eyes toward the heavens, but not necessarily in pious contemplation. Nicolaus Copernicus (1473–1543) launched the strongest attack yet on the Aristotelian view of the universe. He was born near the Baltic coast in Poland. After the death of his father, Copernicus's uncle (a wealthy bishop) assumed responsibility for his education. From the University of Krakow, Copernicus went to Italy to study medicine and law. After learning Greek, he read medieval scientific and humanist texts. Also trained as a doctor and portrait painter, he devoted his life to observation and discovery.

Copernicus's *Concerning the Revolutions of the Celestial Spheres* was not published until he lay dying in 1543, the same year the work of Archimedes was first translated into Latin. Paradoxically, in view of the intense theological debate it would generate, Copernicus dedicated his study to the pope. Copernicus was troubled by the inability of the Ptolemaic system (itself a refraction of the Aristotelian view of the universe) to account for what his own observations, made with the naked eye, told him: that the planets, the moon, and the stars obviously did not move around the earth at the same speed. Nor did they seem to be in the spherical orbits Ptolemy had assigned them. That Mars seemed to vary in brightness particularly perplexed him. What Copernicus observed, in short, contradicted the fundamental assumptions of the Aristotelian and Ptolemaic universe.

Even before Copernicus, some thinkers questioned Aristotelian physics and the Ptolemaic cosmos, but they generally did not venture out of the realm of mere speculation. Nicholas of Cusa (1401–1464), a German bishop and theologian who wrote on astronomy, believed the earth might be in motion, but neither he nor anyone else in the period tried to make mathematical calculations that might prove or reject this bold theory. He suggested the possibility that the sun stands at the center of the universe and, by implication, that the universe is infinite and nonhierarchical in nature, unlimited by Aristotelian layers of spheres. The extraordinary Renaissance artist and humanist Leonardo da Vinci (see Chapter 2), who called wisdom "the daughter of experiment," had also suggested that the earth might move around the sun.

Copernicus concluded that the sun, not the earth, lies at the center of the universe and that the earth rotates on its axis once a day and revolves around the sun once every 365 days. "In the middle of all sits the Sun enthroned," he wrote. "How could we place this luminary in any better position in this most beautiful temple from which to illuminate the whole at once?" Copernicus's postulation was, like his critique of some of Ptolemy's conclusions, not totally original. But his assertions were bold, explicit, and, for many, convincing. Furthermore, they suggested that mathematics could verify astronomical theories.

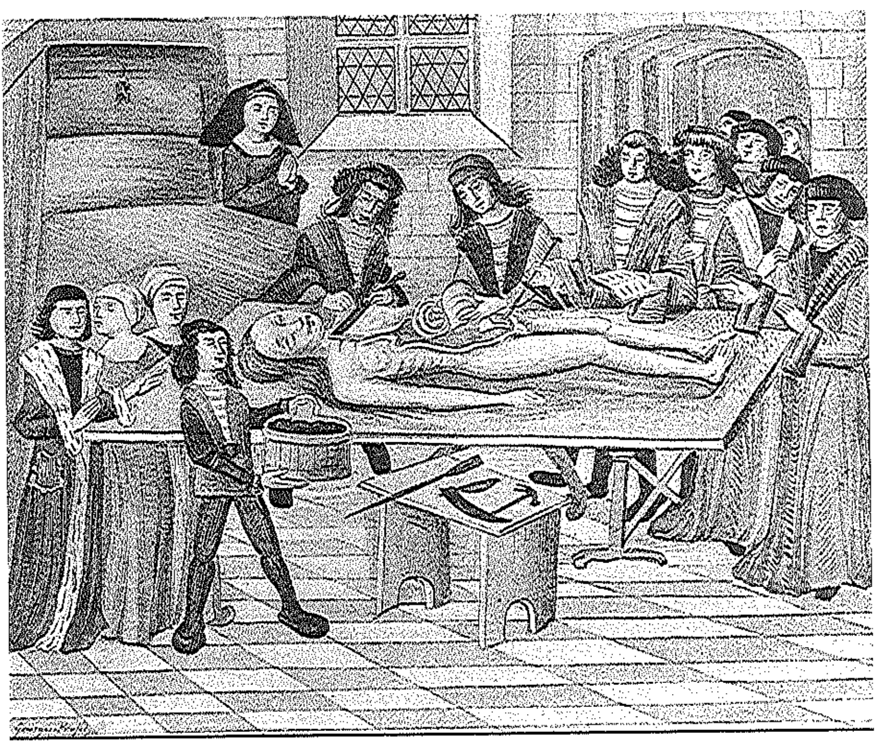
The notion that the earth was just one of many planets rotating in circular orbit around the sun raised shocking questions about the earth's status. This perplexed and angered Catholic, Protestant, and Jewish theologians by seeming to reduce the standing of mankind. It seemed unbelievable that mere mortals peering into the heavens were themselves moving rapidly through the universe. Martin Luther, himself not given to accepting inherited wisdom without skepticism, said of Copernicus, "This fool wants to turn the whole of astronomy upside down!"

Copernicus did just that. Yet he seemed uninterested in carrying out his own systematic observations and made serious errors in some of his calculations. He could not explain why there was no constant wind from the east, which might be expected based on the assumption that the earth moved in that direction around the sun. Copernicus sometimes sought to answer his own doubts by turning to the teachings of the ancients and did not completely abandon the system of celestial spheres postulated by Ptolemy. Copernicus also continued to accept the notion that the spherical universe was finite, and that it perhaps was limited by the stars fixed in the heavens.

The Universal Laws of the Human Body

As scientists began to chart movements in the heavens, some scholars now began to question old assumptions about the human body. They contended that it is subject to the same universal laws that govern celestial and terrestrial motion. The Renaissance had generated interest in human anatomy. Most assumptions about how the body works had been passed down for centuries from the ancient world. Galen (129–c. 210), a Greek contemporary of Ptolemy, was the first person to develop theories about medicine based on scientific experiments. He carried out a number of experiments

Dissecting a cadaver at the University of Montpellier, 1363.



on apes, assuming that animal and human bodies were essentially the same in the arrangement of bodily organs. Like Aristotle, Galen believed that disease followed from an imbalance in the four bodily humors—blood, phlegm, yellow bile, and black bile. He held that two kinds of blood initiated muscle movement and digestion, respectively: bright red blood, which flowed up and down through the arteries, and dark red blood, which could be found in the veins. Doubting Galen's view of anatomy, Andreas Vesalius (1514–1564) published *On the Fabric of the Human Body* (1543). Arguably the founder of modern biological science, Vesalius rejected old explanations for the circulation of blood and began to dissect and study cadavers—in the Middle Ages, the Church had considered this to be sinful—and was the first to assemble human skeletons.

The English scientist William Harvey (1578–1657) largely solved the riddle of how blood circulates. Like the astronomers, he adopted a scientific methodology: "I profess," he wrote, "to learn and teach anatomy not from books but from dissections, not from the tenets of philosophers but from the fabric of nature." Harvey's accomplishment was in the realm of thought and owed virtually nothing to prior inventions. Indeed, he made his discoveries before the invention of the microscope, and he referred only twice in his experiments to a magnifying glass.

Harvey's theory of blood circulation pictured the heart and its valves functioning as a mechanical pump. Yet Harvey, like medieval thinkers, retained a belief that "vital spirits" were to be found in the blood. The long-term consequence of Harvey's work was, as in the case of Vesalius, to undermine further Aristotelian philosophy and medieval science and to help establish a basis for the development of modern biology and medicine in later centuries.

Brahe and Kepler Explore the Heavens

Tycho Brahe (1546–1601), a Danish astronomer, and Johannes Kepler (1571–1630), his German assistant, carried the search for an understanding of the way the universe works to a new stage of scientific knowledge. While studying philosophy at the University of Copenhagen, Brahe became fascinated with the heavens after observing a partial eclipse of the sun. Brahe, an odd-looking nobleman who had lost part of his nose in a duel and had replaced it with a construction of silver and gold alloy perched above his handlebar moustache, built an astronomical observatory on a Danish island.

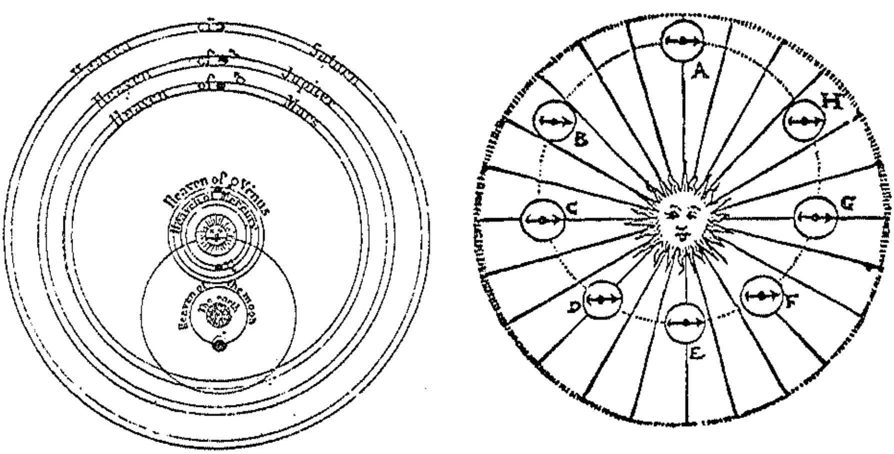
Brahe rejected Copernicus's contention that the earth rotated around the sun. He claimed that if this were true, a cannonball fired from west to east (the direction Copernicus thought the earth moved) would travel farther in that direction, and a weight dropped from a tall tower would strike earth to the west of the tower because of the earth's movement. Brahe came up with a cumbersome compromise explanation that had the five known planets rotating around the sun, which in turn moved around the stationary earth.

In 1572, Brahe observed a bright exploding star. This and a comet sighted five years later irrevocably compromised the Aristotelian view of the universe as unchanging. Brahe compiled extensive data based upon his own observations, systematically charting what he could see of the planetary orbits and using mathematics to locate the position of the planets and stars. At the same time, his rejection of the Copernican view that the sun was the center of the universe and the fact that his calculations were often inaccurate remind us that the Scientific Revolution did not develop in a linear fashion. False turns and setbacks were part of the story.

Johannes Kepler, Brahe's assistant, was the son of a German mercenary soldier and an herb dealer with an interest in astrology (his mother would later be condemned to be burned at the stake for her dabblings in astrology; Kepler saved her life by undertaking a lengthy legal process). Kepler was a dazzling but strange individual: a rigorous astronomer and mathematician as well as a religious mystic and astrologer, who took credit for predicting not only a particularly harsh winter but also peasant uprisings in Germany.

Facing persecution from Lutheran theologians in 1596 because of his Copernican beliefs, Kepler briefly found protection from the Jesuits. But four years later, he was forced to leave a teaching position in Austria because he refused to convert from Lutheranism to Catholicism. Kepler moved to Prague and began to work with Brahe in 1600. On his deathbed, Brahe implored Kepler to complete his observation tables. Holy Roman Emperor Rudolph II, whose interest in science outweighed any concern

(Left) Tycho Brahe's system of planetary rotation, about 1560, *(Right)* Kepler's concept of an attractive force from the sun, early sixteenth century.



that Kepler was Protestant, appointed him to succeed Brahe as imperial mathematician.

Kepler shared Copernicus's belief that observers on earth were moving while the sun stood still. After carefully plotting the orbit of Mars, Kepler concluded that the orbits of the planets were "imperfect"—not circular, but rather elliptical. He also concluded that the planets were affected by some sort of force emanating from the sun. William Gilbert (1544–1603), an English scientist, had published a book on the magnet in 1600, the first study written by a university scholar and informed by laboratory experimentation. Gilbert's investigations of magnetic force provided a model for the development of a modern theory of gravitation. Kepler now decided that it was perhaps magnetic force that attracted the earth and sun to each other. He also determined that tides were the result of the magnetic attraction of the earth and the moon.

Based upon his mathematical calculations, Kepler postulated three laws of planetary motion, which he assumed were determined by the power, or specific magnetic attraction, of the sun. He used observation and mathematical calculations to demonstrate that the planets were a separate grouping with different properties from those of the fixed stars, and that Aristotle's crystalline spheres simply did not exist.

Kepler's discoveries, blows to Aristotelian and medieval science, also suggested that the hand of the prime mover—God—was not required to govern the movement of the planets. Even more than Copernicus's placing of the sun at the center of the universe, Kepler's conclusions challenged the theological assumptions of the Catholic Church. Nonetheless, the Scientific Revolution still occurred within the system of Christian belief. Kepler himself sought to glorify God by demonstrating the consistency, harmony, and order of divine creation as expressed in the working of the universe.

Francis Bacon and the Scientific Method

From England, Sir Francis Bacon (1561–1626), lawyer, statesman, and philosopher, launched a frontal assault on ancient and medieval metaphysics and science. Calling himself "a bellringer who is first up to call others to church," Bacon helped detach science from philosophy. Medieval scholasticism had focused, he argued, on abstract problems that were without practical consequences, such as the question of how many angels could stand on the head of a pin. So, too, had Renaissance humanism. Bacon rejected outright all arguments based on the weight of traditional authority, calling for "a total reconstruction of sciences, arts and all human knowledge."

Bacon carried out few experiments and made no discoveries that could have been considered significant by his own standards (he died after catching a bad cold while carrying out an experiment of marginal value: stuffing snow into a dead chicken). But Bacon announced the dawn of a new era in which humans would gradually begin to understand and then perhaps even overcome their physical environment. Through inductive reasoning—that is, proceeding from observation and experimentation to conclusions or generalizations—the truths of the universe would be revealed by discovery and scientific experiment, not by religion. "Arts and sciences," Bacon wrote in 1620, "should be like mines, where the noise of new works and further advances is heard on every side." Scientists should divide up the toil by specializing and working in cooperation to "overcome the necessities and miseries of humanity." Bacon's renown—he served for three years as King James I of England's Lord Chancellor (before being dismissed for accepting bribes)—helped create interest in science in England, although for the moment this was limited to a small number of people.

Galileo and Science on Trial

On the Italian peninsula, Galileo emerged as the dominant figure of the early stage of the Scientific Revolution. The scion of a wealthy family, he studied medicine and mathematics. Like Copernicus, he taught at the University of Padua, the leading center of scientific learning in Europe, at a time when virtually every other university showed little interest in scientific observation. That Padua was under the protection of Venice, which was hostile to the pope, facilitated its university's precocious role in the development of scientific methodology. Scholars in Padua hotly debated

(*Left*) Sir Francis Bacon. (*Right*) The feisty Galileo at age sixty.

Aristotelian explanations of motion as well as the question of the relationship between the natural sciences and metaphysics, or the nature of being. The latter debate was especially crucial, because on it hinged the question of whether scientific investigation could be independent of the Catholic Church, which considered revealed religion the only source of true knowledge.

New ways of thinking about the heavens, systematic observation, and scientific measurement had played a more significant role in the early stages of the Scientific Revolution than did the development of new technology. The invention of the telescope, however, led to further advances. Upon learning in 1609 that a man in the Netherlands had invented a "spy glass" that could magnify objects many times, Galileo constructed one of his own. This telescope enabled him to study Jupiter's moons, Saturn's spectacular rings, some of the innumerable stars of the Milky Way, and craters on the moon. His observation of spots that seemed to move on the surface of the sun led Galileo to conclude that the sun, too, rotated. That sunspots seemed to change also challenged the traditional view of the static nature of the universe.

Galileo undermined the Aristotelian theories of motion. He demonstrated that the earth was in perpetual rotation and that balls of varying weights will pick up speed at the same rate as they fall, so therefore their speed is not determined by their mass. From such experiments, he developed a theory of inertia: a body moving at a constant speed in a straight line will continue to move until encountering another force. He demonstrated that air and clouds move with the earth as it rotates around the sun, while appearing immobile to an observer also moving with the earth. The rooms in his house that he set aside for experimentation served as the first university laboratory.

Unlike other scholars, Galileo did not disdain seeking practical information from craftsmen and artisans. He consulted workers who built cannons, soldiers who fired them, and people who made compasses, astrolabes, quadrants, and other scientific instruments for navigation. He began to investigate water pumps and other means of regulating rivers, as well as planning the construction of stronger military fortresses. Nonetheless, Galileo did not care whether or not his discoveries reached ordinary people. Moreover, he claimed that "the mobility of the earth is a proposition far beyond the comprehension of the common people." And he believed that the "all-too-numerous vulgar" ought to be kept in darkness, lest they "become confused, obstinate, and contumacious."

At first, Galileo tried to reconcile his findings and those of Copernicus with early Church texts. But the feisty Galileo's insistence that the universe was mathematical in its very structure and subject to laws of mechanics that could be discovered left him open to attacks by ecclesiastical authorities. In 1610, he wrote Kepler, "Here at Padua is the principal professor of theology, whom I have repeatedly and urgently requested to look at the moon and planets through my glass, which he obstinately refused to do. Why are you not here? What shouts of laughter we should have at this glorious folly!" In 1616, the pope condemned Galileo's proposition that the sun is the center of the universe and warned him not to teach it. Undaunted, Galileo published his *Dialogue Concerning Two World Systems—Ptolemaic and Copernican,* in which he taunted Aristotelians by presenting a lengthy dialogue between those espousing the respective systems of Ptolemy and Copernicus. A certain Simplicio took the side of Ptolemy in the dialogues; the character's very name outraged the Church by intimating that a farcical character symbolized the pope. This led to Galileo's condemnation by the Inquisition in 1633. But from house arrest in his villa in the hills above Florence, Galileo continued to observe, experiment, and write, publishing his texts in the Netherlands. When he went blind in 1638, the pope refused to allow him to go to Florence to see a doctor. Despite his blindness, he continued his scientific investigations until his death four years later.

Descartes and Newton: Competing Theories of Scientific Knowledge

Two brilliant thinkers, one French and the other English, accepted Galileo's revision of classical and medieval systems of knowledge. But they offered contrasting theories of scientific knowledge. René Descartes sought to discover the truth through deductive reasoning. Across the English Channel, Isaac Newton followed his countryman Bacon's insistence that the way to knowledge was through scientific experiment. One amazing discovery after another added to the foundations of the "new philosophy" of science. Science played a major part in the quest for demonstrable truth and authority during and following the period of intense social and political turmoil that lasted from the 1590s until the mid-seventeenth century (see Chapter 4).

Descartes and Deductive Reasoning

The reclusive French philosopher René Descartes (1596–1650) shared Bacon's and Galileo's critiques of ancient and medieval learning. But he offered a different methodology for understanding the universe, espousing deductive reasoning, that is, deducing a conclusion from a set of premises, not from scientific observation.

In 1637, Descartes published *Discourse on Method.* In this deeply personal account, he discussed his rejection of the scientific teaching he had encountered as a young man. Too much of what he had learned had been handed down from tradition without critical commentary. He defiantly "resolved no longer to seek any other science than the knowledge of myself, or of the great book of the world."


René Descartes.

Any person, Descartes claimed, has to begin as a blank slate in order to understand the world through deductive reasoning. "I think, therefore I am" (*Cogito, ergo sum*) was his starting point, the postulation of a self-evident truth and the assertion that the ability to think is the basis of human existence. Then each problem has to be separated, he argued, into "as many parts as may be necessary for its adequate solution," moving from the simplest idea to the most difficult, in the same way as a mathematical proof is formulated. Cartesianism (the philosophy of Descartes and his followers) held that the world could be reduced to two substances: mind and matter, "thinking substance" and "extended substance." Matter—defined as an infinite number of particles that fill all space, leaving neither void nor vacuum—could be discovered and described mathematically, as could the laws of motion. Beginning with the certainty of his own existence, Descartes argued that the existence of the material universe and God could be deduced. "Begin with the smallest object, the easiest to understand," he insisted, "and gradually move to a knowledge of those that are the most complex."

This materialist approach to knowledge left little or no room for ancient or medieval learning. As a sign of this break, Descartes published his works in French, identifying Latin with scholasticism and ecclesiastical doctrine. Like Kepler, Descartes viewed God as a benevolent, infinitely powerful clockmaker, who created the universe according to rules that the human mind could discover with proper reasoning. God then stepped back, according to this view, forever absent from the actual workings of what He had created.

Mathematics, Descartes argued, demonstrates "the certainty and self-evidence of its reasonings." It therefore stood as the foundation of all science. Eventually a rule for every phenomenon could be discovered. Descartes thus subordinated experimentation to reason in the quest for truth. One of the stream of savants who went to meet Descartes recalled that "many of them would desire him to shew them his Instruments . . . he would drawe out a little Drawer under his Table, and shew them a paire of Compasses with one of the Legges broken; and then, for his Ruler, he used a sheet of paper folded double."

Sir Isaac Newton (1642–1727) built upon the thought of Kepler, Galileo, and Descartes to effect a bold synthesis of the Scientific Revolution, to which he added his own extraordinary discoveries. Newton's *Principia, The Mathematical Principles of Natural Philosophy* (1687) was the first synthesis of scientific principles. Newton synthesized the empiricism of Galileo and others with the theoretical rigor and logic of Descartes, thereby laying the foundations for modern science, which is based on both theory and experimentation.

Newton conducted some of his experiments while living on his prosperous family's farm. There, sitting under a tree, ruminating about celestial motion, Newton observed a falling apple, which led him to recognize that the force that caused objects to fall to earth was related to planetary motion. Newton demonstrated that earthly and celestial motion are subject to laws that could be described by mathematical formulas, the science of mechanics. Going beyond Kepler's three laws of planetary motion, Newton postulated a theory of universal gravitation, the existence of forces of attraction and repulsion operating between objects. Newton concluded that Kepler's laws of planetary motion would be correct if the planets were being pulled toward the sun by a force whose strength was in inverse proportion to their distance from it. The moon, too, seemed to be drawn to the earth in the same way, while the pull that it exerted determined the ocean tides. Every particle of matter, Newton concluded, attracts every other particle with a force proportional to the product of the two masses, and inversely proportional to the square of the distance that separates them.

Newton combined the insights of his predecessors with his own brilliant discoveries. He correctly calculated that the average density of the earth is about five and a half times that of water, suggested that electrical messages activate the nervous system, and anticipated some of the ideas that two centuries later would form the basis of thermodynamics and quantum theory. Newton was the first to understand that all colors are composed of a mixture of the primary colors of the spectrum. He explained the phenomenon of the rainbow, calculated sound waves, and invented calculus (with Gottfried Leibniz, concurrently but separately). In the late 1660s, he also constructed the first reflecting telescope (previous

Sir Isaac Newton.

telescopes had used a refracting lens). Newton's first paper on optics, published in 1671, proposed that light could be mathematically described and analyzed. Some scientists still consider this paper as the beginning of theoretical physics.

Unlike his predecessors in the development of science, Newton became wealthy and a hero in his own time. He was elected to Parliament in 1689 representing the University of Cambridge, (where he was a professor), became warden of the Royal Mint, and was knighted by the king. However, Newton remained a remote, chaste, humorless figure who published his discoveries with reluctance and initially only when it seemed that rivals might first take the credit for a discovery. He brazenly accused those working on similar problems of copying him, and was ungenerous in acknowledging what he had learned from others. Newton's fame marked the victory of the scientific method, however, over ancient and medieval thought. The eighteenth-century English poet Alexander Pope went so far as to compare Newton's accomplishments with those of God on the first day of creation: "Nature and Nature's laws lay hid in night; God said, Let Newton be! and all was light!" Newton was given a state funeral and buried in London's Westminster Abbey.

The Newtonian synthesis of scientific thinking and discovery spread rapidly from England to the continent. Newton's followers clashed with Cartesians, the followers of Descartes. Newton rejected Descartes's materialism, at least partially because it seemed to leave open the possibility that the world was made up totally of matter and that God did not exist, although the French philosopher never made such an assertion. For his part, Newton believed that God had to intervene from time to time to keep the great clock of creation running, lest it run down. That Newton continued to produce manuscripts on theological questions reflected his own belief that there seemed to be no necessary contradiction between science and religious faith.

Like Descartes, Newton insisted on the explanatory power of abstract reasoning. But despite his postulation of theories that could not be demonstrated by the scientific method, such as his description of gravity as a force that operates between two objects in space, where possible Newton sought to confirm them experimentally. Until at least 1720, some tension remained between the English scientific groups (who insisted on the necessity of experimentation) and their French and German Cartesian counterparts. Yet this was a creative tension, based on a common acceptance of the primacy of scientific inquiry.

The Cartesians found an ally in the Spanish-born Dutch philosopher and mathematician Baruch Spinoza (1632–1677), who also believed that thought and matter formed the two categories of reality. While making his living grinding lenses for glasses, he found both a philosopher's introspective isolation—arguing in a Cartesian manner that human understanding advances through inner reflection—and stimulation from the new physics.

Expelled from the Jewish community of Amsterdam in 1656 for refusing to participate in religious ceremonies, Spinoza, a proponent of human liberation, called for toleration of all beliefs.

The northern German philosopher and mathematician Gottfried Leibniz (1646–1716) agreed with Descartes and rejected Newton's suggestion that God had to intervene from time to time in the operations of the universe, believing this idea to be demeaning to the Creator's divinity. For Leibniz, the universe was, like God, infinite in space and time. The bodies of humans and animals ran like clocks, set in motion, like the universe itself, by God. Leibniz's popularity helped perpetuate the Cartesian challenge to Newton, notably in France. His deductive postulation of the infinite nature of the universe and his Cartesian insistence that God created the universe to run without further divine intervention according to the mathematical laws Newton had discovered became the hallmarks of the "new philosophy."

The Culture of Science

A "culture of science" developed in Western Europe and gradually spread eastward. By the 1660s, letters, newsletters, and periodicals linked Europeans interested in science. Gradually a "republic of science" took shape, spawning meetings, lectures, visits by traveling scholars, correspondence, book purchases, personal libraries, and public experiments. Above all, the formation of learned associations provided a focal point for the exchange of scientific information and vigorous debates over methodology and findings, expanding the ranks of people interested in science. Only a few decades after Galileo's condemnation, Louis XIV of France and Charles II of England granted patronage to institutions founded to propagate scientific learning. Attracted by scientific discoveries, rulers realized that science could be put to use in the interest of their states.

The Diffusion of the Scientific Method

Although most scientific exchange still occurred by correspondence, savants of science also traveled widely seeking to exchange ideas and learn from each other. For example, the Czech scholar Comenius (Jan Komensky, 1592–1670), a member of the Protestant Unity of Czech Brethren, left his native Moravia in the wake of religious persecution during the Thirty Years' War. After more than a decade in Poland, he began to visit scholars in many countries. For seven years, he traveled in the German states, the Netherlands, England, Sweden, and Hungary. Publishing hundreds of works, he proposed that one day scientific knowledge should be brought together in a collaborative form.

Learned associations and scientific societies had already begun to appear in a number of cities, including Rome and Paris, in the 1620s. In

London, a bequest made possible the establishment of Gresham College, which became a center for scientific discussion and research. In Paris, Marin Mersenne (1588–1637), a monk who had translated Galileo's writings into French, stood at the center of a network of vigorous scientific exchange that cut across national boundaries of states. He organized informal gatherings, attended by, among others, Blaise Pascal (1623–1662), a gloomy young physicist and mathematician who originated the science of probability.

In England, above all, the culture of science became part of public life during the period from 1640 to 1660, with the vocabulary of science joining the discourse of the English upper classes. Newton's prestige further spurred interest in scientific method. In several London coffeehouses, Newtonians offered "a course of Philosophical Lectures on Mechanics, Hydrostatis, Pneumatics [and] Opticks." Exchanges, debates, and even acrimonious disputes reached an ever wider scholarly audience. In England, pamphlets and books on scientific subjects were published in unprecedented numbers.

The Royal Society of London for Improving Natural Knowledge was formed in 1662 under the patronage of Charles II. Its diverse membership, which included merchants, naval officers, and craftsmen, reflected the growing interest in science in England. Members included Edmund Halley (1656–1742), an astronomer who catalogued and discovered the actual movement of the stars and who also discovered the comet that bears his name; the philosopher John Locke (1632–1704), founder of British empiricism, who held that laws of society, like those of science, could be discovered; and Christopher Wren (1632–1723), a versatile architect who rebuilt some of London's churches (including St. Paul's Cathedral) in the wake of the fire of 1666, but who was also a mathematician and professor of astronomy.

The Royal Society, to which Newton dedicated *Principia* and of which he served as president, took its motto from one of the letters of the Roman writer Horace: "The words are the words of a master, but we are not forced to swear by them. Instead we are to be borne wherever experiment drives us." The Royal Society's hundred original members doubled in number by 1670, its weekly meetings attracting visiting scholars. The *Philosophical Transactions of the Royal Society* published some of the most important work of members and foreign correspondents, especially in the field of mathematics.

The natural philosopher Margaret Cavendish, the duchess of Newcastle (1623–1673), participated in debates about matter and motion, the vacuum, magnetism, and the components of color and fire. The author of books on natural philosophy, as well as a number of plays and poems, Cavendish also hosted the "Newcastle circle," an informal gathering of distinguished scientists that received Descartes. But she worked in isolation, which she attributed not only to the fact that she was shy, but to her sex. Despite the

The Newcastle circle hosted by the duke and duchess of Newcastle. Margaret Cavendish, the duchess, is seated on the far right crowned with laurels.

evidence of her own achievements, she accepted, at least in her early years, the contemporary assumptions that women had smaller and softer brains than men, and thus were somehow unfit for science and philosophy. Few men of science would have agreed with the assertion in 1673 by one of Descartes's disciples in France that "the mind has no sex." This bold statement reflected Descartes's belief that thought transcended gender differences—and, therefore, having sense organs equal to men's, women should be recognized as their equals. But although Cavendish was permitted to attend one session, women were formally banned from the Royal Society—this would last until 1945—and they were excluded from English universities.

Yet as an interest in scientific theories and discoveries became influential among the educated upper classes, women also wanted to be informed about science. Several women assisted their husbands in scientific experiments. In Italy, it was more common for women to participate in the scientific life of their cities. Laura Bassi Veratti (1711–1778) studied philosophy at the University of Bologna and was elected to the Academy of Sciences, where she regularly presented her work—although she published very little. She received the title of university lecturer, but because of her gender she was not allowed to teach in public, only at home (which was very common in Italy). Later, however, after having studied mathematics, Bassi was named professor of experimental physics, experimented with fluid mechanics and electricity (perhaps even before Benjamin Franklin conducted his

Testelin's tapestry of the establishment of the French Royal Academy of Science, 1666, and the Foundation of the Observatory, 1667.

studies), was allowed in the last years of her life to teach in public, and thanks to surprising patronage from prelates in Rome was even able to gain access to the scientific studies that the pope had placed on the Index of Forbidden Ideas or Books. Laura Bassi remained an active participant in the scientific community.

In 1666, the French Royal Academy of Science held its first formal meeting in Paris. Like the English Royal Society, the French Academy enjoyed the patronage of the monarchy, which even provided the Academy with an astronomical observatory. Branches of the Academy began in several provincial cities. Unlike members of its English counterpart, those in the French Academy spent much time eating and drinking—one of them complained that too much time was wasted at the fancy dinners that preceded scholarly discussion.

Although some writers deliberately had used Latin because they believed that knowledge ought to remain the preserve of the educated few, with the gradual ebbing of Latin as the language of science, language barriers became a greater obstacle to the diffusion of ideas and research. Galileo had written in Italian to attract a wider audience among the elite, but also to remove science from Latin, the language of religious discourse. Newton wrote *Principia* in Latin, in part because only then could his work be read by most continental scholars. Newton's *Optics*, by contrast, appeared first in English, then in Latin and French translations. Gradually during the eighteenth century, each country's vernacular became the language of its scientists.

By the end of the seventeenth century, the ideas of Descartes had overcome Calvinist opposition to find their way into Dutch university curricula. But the further east one went in Europe, the weaker was the impact of the Scientific Revolution. Scientific inquiry lagged in Poland, in part because of the success of the Catholic Reformation, which restricted the free flow of scholarly thought. Several printing houses in Gdańsk owned by Protestants began publishing scientific works in the second half of the seventeenth century. Leibniz enjoyed popularity in the Habsburg domains, at least partially because he served several German rulers in a diplomatic capacity, and perhaps also because his contagious optimism and belief that God had preordained harmony found resonance in the diverse and scattered kingdom. Nonetheless, theological and devotional literature still dominated the shelves of university, monastic, and imperial libraries. The few publications on science remained strongly Aristotelian.

Some savants in the East did become aware of the debates in the West on the scientific method. Protestant thinkers in Hungary and Silesia, for example, were gradually exposed to the ideas of Bacon and Descartes by traveling scholars from Western Europe, and a few Hungarians and Silesians learned of the new ideas by visiting Dutch universities. Some Bohemian and Polish nobles began to include books on the new science in their private libraries, one of which eventually comprised over 300,000 volumes and 10,000 manuscripts. Theoretical and practical astronomical work spread in the Habsburg lands, carried on in some cases by Jesuits. Mathematics, optics, and problems of atmospheric pressure, too, were the focus of debate. Holy Roman Emperor Ferdinand III (ruled 1637–1657) studied military geometry, constructing arithmetic toys for his children.

Russia's distant isolation from Western culture was compounded by the Orthodox Church's antipathy toward the West and, therefore, opposition to scientific experimentation. There was, to be sure, acceptance of some practical knowledge from the West, for example relating to the military, mining, or metallurgy, which largely arrived with foreign merchants and adventurous craftsmen. Seventeenth-century Russia had no gifted scientists and no scientific societies. Until the reign of Peter the Great, virtually all books published in Russia were devotional in character, and Russian culture was essentially that of a monastery. Foreign books began to appear at court only after about 1650, many arriving from Poland and Ukraine. At that point, however, the Orthodox Church, having suffered a schism, launched another campaign against Western ideas, denouncing secular knowledge as heresy and science as the work of the Antichrist. But gradually some nobles began to be exposed to ideas from the natural sciences. These were the Russian nobles who were dissatisfied with Church learning and eager to know more, for example, about the geography of their own expanding state. The literate classes in Russia would thereafter in many ways remain divided between those interested in ideas coming from the West (most of what was known in the West was available in Russia by

1725) and those who rejected them in the name of preserving what they considered Russia's uniqueness as the most dominant Slavic state.

The Uses of Science

The seventeenth-century Scientific Revolution was above all a revolution in thought. Technological inventions that would change the way people lived lay for the most part in the future. But during the second half of the seventeenth century, scientific experimentation led to the practical application of some discoveries. Thanks to Newton, longitude could now be easily established and ocean tides accurately charted. Voyages of discovery, commerce, and conquest to the Americas increased the demand for new navigational instruments. Dutch scientists and craftsmen led the way in producing telescopes, microscopes, binoculars, and other scientific instruments.

But gradually, too, physicians, engineers, mariners, instrument makers, opticians, pharmacists, and surveyors, many of them self-educated, began to apply the new discoveries to daily life. Robert Hooke (1635–1703), another member of the Royal Society, improved the barometer, which measures atmospheric pressure, and augmented the power of the microscope by adding multiple lenses. This allowed him to study the cellular structure of plants. Biologists began to collect, categorize, dissect, and describe fossils, birds, and exotic fish, adding to contemporary understanding of the richness and complexity of the world around them.

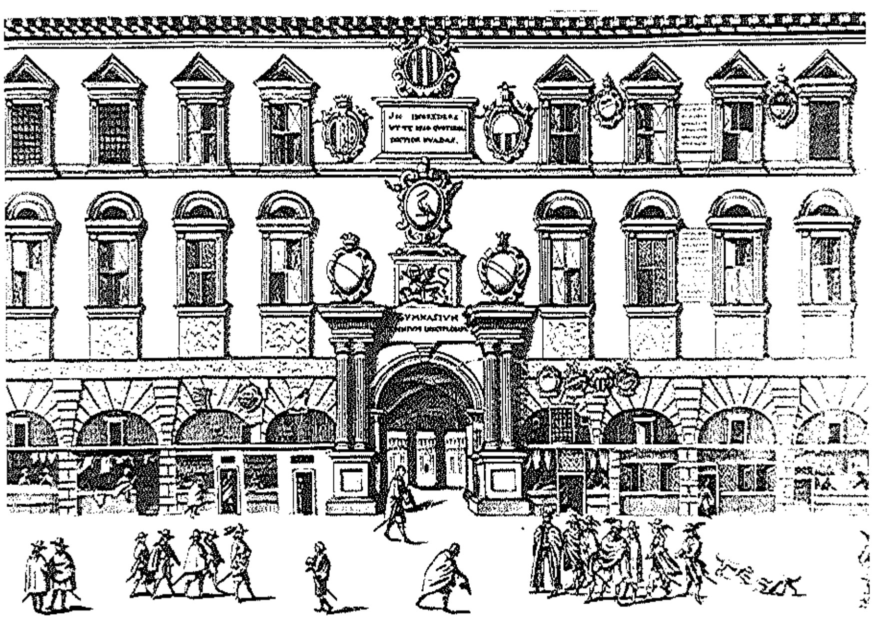
As Francis Bacon had predicted, governments began to tap science in the service of the state. Absolute monarchs on the continent sought out scientists to produce inventions that would give them commercial and military advantages over their rivals. In France, Jean-Baptiste Colbert, Louis XIV's minister of finance, sought to steer the Royal Academy of Science toward the study of what he considered useful subjects that might benefit French commerce and industry, ordered the collection of statistics, and commissioned people to make reliable maps of the provinces and colonies. English government officials also began to apply statistics to administrative and social problems.

Tsar Peter the Great (see Chapter 7) was convinced by his trip to Western Europe that Russia would have to borrow from the West. He corresponded with Leibniz, who convinced him that empirical science, along with the creation of a system of education, would bring progress. The tsar wanted to refute the Western view that "[Russians] are barbarians who disregard science." Peter's campaign of westernization, which included opening his country to Western scientific ideas, made Russia a great power. The sciences that interested Peter were those that were useful in statemaking: mechanics, chemistry, and mathematics all aided in building ships and improving artillery. Peter established the Russian Academy of Sciences and the Moscow School of Mathematics and Navigation, which produced the first generation of Russian explorers, cartographers, and astronomers.

As scientific discoveries led more people to doubt religious authority that was based on faith alone, points of tension not surprisingly continued to emerge between science and religion. This was particularly the case with the Catholic and Orthodox Churches. There seemed to be a close association between Protestant countries and advances in science, given the precocious role of England and, to a lesser extent, the Netherlands in the emergence of a culture of science. This contributed to the debate over whether Protestantism itself was more conducive to scientific inquiry.

Theological concerns still dominated the curricula at most universities, despite the role of science at the University of Padua, and the University of Cambridge, where by the 1690s both Newton's theories and those of Descartes were taught. Universities contributed relatively little to the diffusion of the scientific method. During the seventeenth century as a whole, their enrollments declined as the European population stagnated. In Catholic countries, canon law, and in Protestant states, civil law predominated in universities, which trained Church and state officials, respectively. The number of German universities more than doubled to about forty during the seventeenth century. The impetus for their creation came from Lutheranism and Calvinism, however, not from an interest in science.

The University of Padua in Italy, pictured at about the time Galileo taught there.

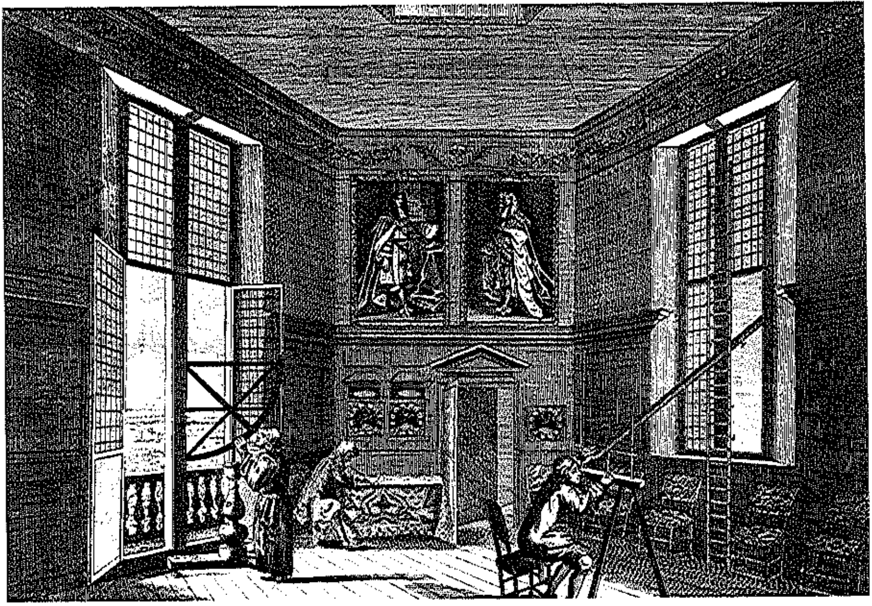


Catholic universities continued to be the most traditional. Following Descartes's death in 1650, the University of Paris, which had about 30,000 students and was the largest university on the continent, forbade a funeral oration for him. Almost three decades later, the archbishop of Paris declared that "in physics it is forbidden to deviate from the principles of the physics of Aristotle . . . and to attach oneself to the new doctrines of Descartes." The University of Paris continued to exclude the new philosophy until the 1730s. Experimental physics as well as botany and chemistry were absent from university study throughout Europe.

The salient role of Protestants in the diffusion of scientific method reflected differences between the theological stance of the Catholic Church and the more liberal ethos of the Protestant Reformation. Catholic theologians left little room for innovation or experimentation. The Protestant belief that an individual should seek truth and salvation in his or her own religious experience through a personal interpretation of the Bible encouraged skepticism about doctrinal theology. The emphasis on individual discovery seemed to lead naturally to empiricism. While Protestant theologians also could be rigid and unyielding, there was no Protestant equivalent to the papal Index of Forbidden Ideas or Books or the mechanism of the Inquisition.

Scientists in Catholic states, confronted by ecclesiastical denunciations or by reports of miracles that seemed to fly in the face of logic, found support in Protestant lands. The Protestant Dutch Republic, fighting a long civil war against Spanish rule, emerged as a center of toleration, where most books could be published. When Descartes learned of the condemnation of Galileo's work, he fled France for the Netherlands, where he published *Discourse on Method.* Francis Bacon had been among the first to associate the Scientific Revolution with the Protestant Reformation. Indeed, many Protestants believed that scientific discovery would lead to a better world and that the wonders of nature were there to be discovered and to give greater glory to God. Yet Jesuits in Bohemia protected Kepler (who had faced persecution from Protestant theologians), provided he limited himself to speculation about astronomy and mathematics and avoided what they considered to be theological questions.

The development of a scientific view of the world in England may be better understood in the context of decades of social, intellectual, and political crisis during the mid-seventeenth century. The campaigns of Parliament and of Puritanism against Charles I's seeming moves toward absolutism and Catholicism attracted political and religious reformers (see Chapter 6). Many who considered the Catholic Church an obstacle to scientific inquiry opposed Charles I as they sought a climate of freedom. The reformers' triumph in the English Civil War may have emboldened Newton and other proponents of the new philosophy. Moderate Anglicans, like the Puritans before them, insisted that science could bring progress. They encouraged the creation of the Royal Observatory, founded by Charles II



Astronomers using a telescope at the Royal Observatory of London.

at Greenwich in 1675. Newton and other members of the Royal Society almost unanimously supported the exile of the Catholic King James II to France and the Glorious Revolution of 1688. Censorship was relatively rare in England, where political and ecclesiastical authority was not so centralized.

By way of contrast, state censorship, encouraged by the Catholic Church, had formally begun in France in 1623, five years after the sovereign law court of Toulouse had ordered a defrocked monk burned at the stake for denouncing belief in miracles after studying at the University of Padua. Thereafter, each new manuscript had to be submitted to a royal office for authorization to be published. Six years later, separate offices were established for literature, science, and politics, with ecclesiastics having veto power over books treating religious subjects.

Yet, to be sure, not all churchmen in France adamantly waged a war on science. Some French Jesuits were open-minded about the scientific method. Jansenists, forming a dissident movement within the Church, also favored scientific discovery, discussion, and debate (see Chapter 7).

Consequences of the Scientific Revolution

The Scientific Revolution seemed to push theology into the background. Even though the earliest exponents of scientific method never doubted

God's creation of the universe, the idea that mankind might one day master nature shocked many Church officials. Descartes's materialism seemed to suggest that humanity could live independently of God. Faith in the scientific method indeed had distinct philosophical consequences: "If natural Philosophy, in all its parts, by pursuing this method, shall at length be perfected," Newton reasoned, "the bounds of moral philosophy will also be enlarged." The English poet John Donne had already come to the same conclusion in 1612. "The new philosophy," he wrote prophetically, "calls all in doubt."

The men and women of science espoused the application of the scientific method to the study of nature and the universe. It was but a short step to subjecting society, government, and political thought to similar critical scrutiny. The English philosopher John Locke claimed that society was, as much as astronomy, a discipline subject to the rigors of the scientific method. Moreover, the Scientific Revolution would ultimately help call absolutism into doubt by influencing the philosophes, the thinkers and writers of the eighteenth-century Enlightenment. The philosophes' belief in the intrinsic value of freedom and their assertion that people should be ruled by law, not rulers, would challenge the very foundations of absolutism.

CHAPTER 9

ENLIGHTENED THOUGHT AND THE REPUBLIC OF LETTERS

"What is the Enlightenment?" wrote the German philosopher Immanuel Kant. His response was "*Dare to know!* Have the courage to make use of your own understanding," as exciting a challenge today as in the eighteenth century. During that period of contagious intellectual energy and enthusiastic quest for knowledge, the philosophes, the thinkers and writers of the Enlightenment, espoused intellectual freedom and the use of reason in the search for progress. Unlike most scientists of the preceding period, they wanted their ideas to reach the general reading public. Education therefore loomed large in this view of their mission. Their approach to education was not limited to formal schooling, but instead took in the development of the individual and the continued application of critical inquiry throughout one's life.

The Enlightenment began in Paris but extended to much of Western Europe, including the German states, the Dutch Republic, Great Britain, and as far as North America. The works of the philosophes reached Poland and Russia. Orthodox Christian intellectuals carried the Enlightenment's celebration of science and humanism into the Balkans. The philosophes' writings helped confirm French as the language of high culture in eighteenth-century Europe. Indeed, it was reported from Potsdam that at the court of Frederick the Great of Prussia "the language least spoken is German." But French was hardly the only language of philosophic discourse. In Italy, those influenced by the new thinking used the ideas of the philosophes to attack clerical and particularly papal influence in political life. In Britain, the philosopher David Hume and economist Adam Smith, father of free-market liberalism, represented the thought of the "Scottish Enlightenment."

The Enlightenment can be roughly divided into three stages. The first covers the first half of the eighteenth century and most directly reflects the