C H A P T E R

16

Toward a New Heaven and a New Earth: The Scientific Revolution and the Emergence of Modern Science

CHAPTER OUTLINE

- Background to the Scientific Revolution
- Toward a New Heaven: A Revolution in Astronomy
- Advances in Medicine
- Women in the Origins of Modern Science
- Toward a New Earth: Descartes, Rationalism, and a New View of Humankind
- The Scientific Method
- Science and Religion in the Seventeenth Century
- The Spread of Scientific Knowledge
- Conclusion

FOCUS QUESTIONS

- What developments during the Middle Ages and Renaissance contributed to the Scientific Revolution of the seventeenth century?
- What did Copernicus, Kepler, Galileo, and Newton contribute to a new vision of the universe, and how did it differ from the Ptolemaic conception of the universe?
- What role did women play in the Scientific Revolution?
- What problems did the Scientific Revolution present for organized religion, and how did both the church and the emerging scientists attempt to solve these problems?
- How were the ideas of the Scientific Revolution disseminated, and what impact did they have on society?

IN ADDITION to the political, economic, social, and international crises of the seventeenth century, we need to add an intellectual one. The Scientific Revolution questioned and ultimately challenged conceptions and beliefs about the nature of the external world and reality that had crystallized into a rather strict orthodoxy by the Late Middle Ages. Derived from the works of ancient Greeks and Romans and grounded in Christian thought, the medieval worldview had become a formidable one. No doubt, the breakdown of Christian unity during the Reformation and the subsequent religious wars had created an environment in which Europeans had become accustomed to challenging both *the ecclesiastical and political realms. Should it surprise us that a challenge to intellectual authority soon followed?*

The Scientific Revolution brought Europeans a new way of viewing the universe and their place in it. The shift from an earth-centered to a sun-centered cosmos had an emotional as well as an intellectual effect upon those who understood it. Thus, the Scientific Revolution, popularized in the eighteenth-century Enlightenment, stands as the major force in the transition to the largely secular, rational, and materialistic perspective that has defined the modern Western mentality since its full acceptance in the nineteenth and twentieth centuries.

The transition to a new worldview was not an easy one, however. In the seventeenth century, the Italian scientist Galileo, an outspoken advocate of the new worldview, found that his ideas were strongly opposed by the authorities of the Catholic church. Galileo's position was clear: "I hold the sun to be situated motionless in the center of the revolution of the celestial bodies, while the earth rotates on its axis and revolves about the sun." Moreover, "nothing physical that sense-experience sets before our eyes . . . ought to be called in question (much less condemned) upon the testimony of Biblical passages." But the church had a different view, and in 1633, Galileo, now sixty-eight and in ill health, was called before the dreaded Inquisition in Rome. He was kept waiting for two months before he was tried and found guilty of heresy and disobedience. Completely shattered by the experience, he denounced his errors: "With a sincere heart and unfeigned faith I curse and detest the said errors and heresies contrary to the Holy Church, and I swear that I will nevermore in future say or assert anything that may give rise to a similar suspicion of me." Legend holds that when he left the trial room, Galileo muttered to himself: "And yet it does move!" In any case, Galileo had been silenced, but his writings remained, and they began to spread through Europe. The Inquisition had failed to stop the spread of the new ideas of the Scientific Revolution.

In one sense, the Scientific Revolution was not a revolution. It was not characterized by the explosive change and rapid overthrow of traditional authority that we normally associate with the word revolution. *The Scientific Revolution did overturn centuries of authority, but only in a gradual and piecemeal fashion. Nevertheless, its results were truly revolutionary. The Scientific Revolution was a key factor in setting Western civilization along its modern secular and material path.*

◆ Background to the Scientific Revolution

To say that the Scientific Revolution brought about a dissolution of the medieval worldview is not to say that the Middle Ages was a period of scientific ignorance. Many educated Europeans took an intense interest in the world around them since it was, after all, "God's handiwork" and therefore an appropriate subject for study. Late medieval scholastic philosophers had advanced mathematical and physical thinking in many ways, but the subjection of these thinkers to a strict theological framework and their unquestioning reliance on a few ancient authorities, especially Aristotle and Galen, limited where they could go. Many "natural philosophers," as medieval scientists were called, preferred refined logical analysis to systematic observations of the natural world. A number of historians have argued, however, that some of the natural philosophers developed ideas that came to fruition in the seventeenth century. These historians have pointed out, for example, that Galileo's development of the science of mechanics was grounded upon the work of fourteenth-century scholastics. And yet, as other scholars have noted, there was still a great contrast between the "theoretical" approach of the scholastics and the "hands-on" experiments of Galileo that enabled him to make his case.

The historical debate over the issue of late medieval influence on the Scientific Revolution reminds us that historians have had a difficult time explaining the causes of the Scientific Revolution. They have pointed out, however, that a number of changes and advances in the fifteenth and sixteenth centuries may have played a major role in helping natural philosophers abandon their old views and develop new ones.

Whereas medieval scholars had made use of Aristotle, Galen, and Ptolemy in Latin translations to develop many of their positions in the fields of physics, medicine, and astronomy, the Renaissance humanists had mastered Greek as well as Latin and made available new works of Galen, Ptolemy, and Archimedes as well as Plato and the pre-Socratics. These writings made it apparent that even the unquestioned authorities of the Middle Ages, Aristotle and Galen, had been contradicted by other thinkers. The desire to discover which school of thought was correct stimulated new scientific work that sometimes led to a complete rejection of the classical authorities. We know that Copernicus, for example, founder of the heliocentric theory, had read in Plutarch (discovered by the Renaissance) that Philolaus and a number of other ancients had believed that it was the earth and not the sun that moved.

Renaissance artists have also been credited with making an impact on scientific study. Their desire to imitate nature led them to rely upon a close observation of nature. Their accurate renderings of rocks, plants, animals, and human anatomy established new standards for the study of natural phenomena. At the same time, the "scientific" study of the problems of perspective and correct anatomical proportions led to new insights. "No painter," one Renaissance artist declared, "can paint well without a thorough knowledge of geometry."[1] Renaissance artists were frequently called upon to be practicing mathematicians as well. Leonardo da Vinci devised "war machines" while Albrecht Dürer made designs for the fortifications of cities.

Although most of these artistic designs for technical innovations were not intended for actual use and remained on paper, mathematicians, military engineers, naval architects, and navigators were having to deal with such practical problems as how to navigate in unknown seas, how to compute the trajectories of cannonballs for more effective impact, and how to calculate the tonnage of ships accurately. These technical problems served to stimulate scientific activity because all of them required careful observation and accurate measurements. The fifteenth and sixteenth centuries witnessed a proliferation of books dedicated to machines and technology, all of which espoused the belief that innovation in techniques was necessary. The relationship between technology and the Scientific Revolution is not a simple one, however, for many technological experts did not believe in abstract or academic learning. Indeed, many of the technical innovations of the Middle Ages and Renaissance were accomplished outside the universities by people who emphasized practical rather than theoretical knowledge. In any case, the invention of new instruments and machines, such as the telescope and microscope, often made new scientific discoveries possible. Above all, the printing press had an indirect, but crucial role in spreading innovative ideas quickly and easily.

Mathematics, which played such a fundamental role in the scientific achievements of the sixteenth and seventeenth centuries, was promoted in the Renaissance by the rediscovery of the works of ancient mathematicians and the influence of Plato (see Chapter 12), who had emphasized the importance of mathematics in explaining the universe. While mathematics was applauded as the key to navigation, military science, and geography, the Renaissance also held the widespread belief that mathematics was the key to understanding the nature of things. According to Leonardo da Vinci, since God eternally geometrizes, nature is inherently mathematical: "Proportion is not only found in numbers and measurements but also in sounds, weights, times, positions, and in whatsoever power there may."[2] Moreover, mathematical reasoning was seen as promoting a degree of certainty that was otherwise impossible. In the words of Leonardo da Vinci: "There is no certainty where one can neither apply any of the mathematical sciences nor any of those which are based upon the mathematical sciences."[3] Copernicus, Kepler, Galileo, and Newton were all great mathematicians who believed that the secrets of nature were written in the language of mathematics.

A final factor in the origins of the Scientific Revolution, the role of magic, has been the object of heated scholarly debate. Renaissance magic (see Chapter 12) was the preserve of an intellectual elite from all of Europe (see the box on p. 463). By the end of the sixteenth century, Hermetic magic had become fused with alchemical thought into a single intellectual framework. According to this tradition, the world was a living embodiment of divinity. Humans, who it was believed also had that spark of divinity within, could use magic, especially mathematical magic, to understand and dominate the world of nature or employ the powers of nature for beneficial purposes. Was it Hermeticism, then, that inaugurated the shift in consciousness that made the Scientific Revolution possible, since the desire to control and dominate the natural world was a crucial motivating force in the Scientific Revolution? One scholar has argued:

> It is a movement of the will which really originates an intellectual movement. A new center of interest arises, surrounded by emotional excitement; the mind turns where the will has directed it and new attitudes, new discoveries follow. Behind the emergence of modern science there was a new direction of the will toward the world, its marvels, and mysterious workings, a new longing and determination to understand those workings and to operate with them.[4]

"This time," the author continues, "the return to the occult [Hermetic tradition] stimulates the genuine science."[5] Histories of the Scientific Revolution frequently overlook the fact that the great names we associate with the revolution in cosmology—Copernicus, Kepler, Galileo, and Newton—all had a serious interest in Hermetic ideas and the fields of astrology and alchemy. The mention of these names also reminds us of one final consideration in the origins of the Scientific Revolution: it largely resulted from the work of a handful of great intellectuals.

◆ Toward a New Heaven: A Revolution in Astronomy

The greatest achievements in the Scientific Revolution of the sixteenth and seventeenth centuries came in those fields most dominated by the ideas of the Greeks—astronomy, mechanics, and medicine. The cosmological views of the Late Middle Ages had been built upon a synthesis of the ideas of Aristotle, Claudius Ptolemy (the greatest astronomer of antiquity who lived in the second century A.D.), and Christian theology. In the resulting Ptolemaic or geocentric conception, the universe was seen as a series of concentric spheres with a fixed or motionless earth as its center. Composed of the material substances of earth, air, fire, and water, the earth was imperfect and constantly changing. The spheres that surrounded the earth were made of a crystalline, transparent substance and moved in circular orbits around the earth. Circular movement, according to Aristotle, was the most "perfect" kind of motion and hence appropriate for the "perfect" heavenly bodies thought to consist of a nonmaterial, incorruptible "quintessence." These heavenly bodies, pure orbs of light, were embedded in the moving, concentric spheres and in 1500 numbered ten. Working outward from the earth, eight spheres contained the moon, Mercury, Venus, the

Magic and Science: The Case of Girolamo Cardano

Girolamo Cardano or Jerome Cardan (1501–1576) was a very important figure in the history of mathematics. He also became a physician and professor of medicine at Pavia in 1547. Like many other intellectuals in the sixteenth century, Cardano was a student of magic and astrology. In this selection taken from his autobiography, The Book of My Life, *Cardano discusses the presence in his life of what we would call paranormal powers, including prescient dreams, extrasensory perception, and intuitive flashes of direct understanding.*

Girolamo Cardano, *The Book of My Life*

I am conscious that some influence from without seems to bring a murmuring sound to my ear from precisely that direction or region where some one is discussing me. If this discussion be fair, the sound seems to come to rest on the right side; or, if perchance it approaches from the left, it penetrates to the right and becomes a steady hum. If, however, the talk be contentious, strangely conflicting sounds are heard; when evil is spoken, the noise rests in the left ear, and comes from the quarter exactly whence the voices of my detractors are making disturbance, and, accordingly, may approach from any side of my head. . . . Very often when the discussion about me has taken place in the same city, it has happened that the vibration has scarcely ceased before a messenger has appeared who addresses me in the name of my detractors. But if the conversation has taken place in another state and the messenger should appear, one has but to compute the space of time which had elapsed between the discussion and the beginning of the messenger's journey, and the moment I heard the voices and the time of the discussion itself will fall out the same. . . .

A few years later, eight perhaps, that is, about 1534, I began to see in my dreams the events shortly to come to pass. If these events were due to happen on the day following the dream, I used to have clear and defined visions of them just after sunrise, so that even on occasion I saw the motion for my admission to the College of Physicians straightway brought to vote, to a decision, and the motion lost. I dreamed, as well, that I was about to obtain my appointment to the professorship at Bologna. This manifestation by dreams ceased in the year just preceeding the cessation of the former manifestation, that is, about 1567. . . . And so it had lasted about thirty-three years.

A third peculiarity is an intuitive flash of direct knowledge. This I employed with gradually increasing advantage. It originated about the year 1529; its effectiveness was increased but it could never be rendered infallible, except toward the close of 1573. For a period between the end of August of that year and the beginning of September 1574, and particularly, as it seems to me, now in this year 1575, I have considered it infallible. It is, moreover, a gift which has not deserted me, and it replaces the power of those two latter faculties which did; it prepares me to meet my adversaries, and for any pressing necessity. Its component parts are an ingeniously exercised employment of the intuitive faculty, and an accompanying lucidity of understanding.

sun, Mars, Jupiter, Saturn, and the fixed stars. The ninth sphere imparted to the eighth sphere of the fixed stars its motion, and the tenth sphere was frequently described as the prime mover that moved itself and imparted motion to the other spheres. Beyond the tenth sphere was the Empyrean Heaven—the location of God and all the saved souls. This Christianized Ptolemaic universe, then, was a finite one. It had a fixed end in harmony with Christian thought and expectations.

This medieval, geocentric conception of the universe was one that accorded well with both Christianity and common sense at that time. God and the saved souls were at one end of the universe while humans were at the center. They had been given power over the earth, but their real purpose was to achieve salvation. To ordinary people, this conception of the universe also appeared sensible as they looked up at the night sky. The huge earth could easily be seen as motionless and surrounded by ethereal heavenly bodies circling around it.

This conception, however, did not satisfy professional astronomers who wished to ascertain the precise paths of the heavenly bodies across the sky. Finding that their observations did not always correspond to the accepted scheme, astronomers tried to "save appearances" by developing an elaborate system of devices. They proposed, for example, that the planetary bodies traveled on epicycles, concentric spheres within spheres, that would enable the paths of the planets to correspond more precisely to observations while adhering to Aristotle's ideas of circular planetary movement.

Copernicus

Although Nicolaus Copernicus (1473–1543) received a doctorate in canon law and spent the last thirty years of his life as canon of a cathedral, mathematics and astronomy occupied most of his time. He had studied both subjects first at Cracow in his native Poland and later at the Italian universities of Bologna and Padua. Before he left Italy in 1506, he had become aware of ancient views that contradicted the Ptolemaic, earth-centered conception of the universe. Between 1506 and 1530, he completed the manuscript of his famous book, *On the Revolutions of the Heavenly Spheres,* but his own timidity and fear of ridicule from fellow astronomers kept him from publishing it until May 1543, shortly before his death.

Copernicus was not an accomplished observational astronomer and relied for his data on the records of his predecessors. But he was a mathematician who felt that Ptolemy's geocentric system was too complicated and failed to accord with the observed motions of the heavenly bodies (see the box on p. 466). Copernicus hoped that his heliocentric or sun-centered conception would offer a simpler, more accurate, and more elegant explanation for previously observed phenomena.

Using elaborate astronomical and mathematical calculations, Copernicus argued in his book that the universe consisted of eight spheres with the sun motionless at the center and the sphere of the fixed stars at rest in the eighth sphere. The planets revolved around the sun in the order of Mercury, Venus, the earth, Mars, Jupiter, and Saturn. The moon, however, revolved around the earth. Moreover, according to Copernicus, what appeared to be the movement of the sun and the fixed stars around the earth was really explained by the daily rotation of the earth on its axis and the journey of the earth around the sun each year.

Copernicus, however, was basically conservative. He did not reject Aristotle's principle of the existence of heavenly spheres moving in circular orbits. As a result, when he put forth the calculations to prove his new theory, he retained Ptolemy's epicycles and wound up with a system almost as complicated as that of the Alexandrian astronomer.

Nevertheless, the shift from an earth-centered to a sun-centered system was significant and raised serious questions about Aristotle's astronomy and physics despite Copernicus's own adherence to Aristotle. It also seemed to create uncertainty about the human role in the universe as well as God's location. Protestant reformers, adhering to a literal interpretation of Scripture, were the first to attack the new ideas. Martin Luther thundered against "the new astrologer who wants to prove that the earth moves and goes round. . . . The fool wants to turn the whole art of astronomy upside down. As Holy Scripture tells us, so did Joshua bid the sun stand still and not the earth." Luther's cohort at Wittenberg, Philip Melanchthon condemned Copernicus as well:

> The eyes are witness that the heavens revolve in the space of twenty-four hours. But certain men, either from the love of novelty, or to make a display of ingenuity, have concluded that the earth moves, and they maintain that neither the eighth sphere [of the fixed stars] nor the sun revolves. . . . Now it is a want of honesty and decency to assert such notions publicly, and the example is pernicious. It is the part of a good mind to accept the truth as revealed by God and to acquiesce in it.[6]

The Catholic church remained silent for the time being; it did not denounce Copernicus until the work of Galileo appeared. The denunciation came at a time when an increasing number of astronomers were being attracted to Copernicus's ideas.

MEDIEVAL CONCEPTION OF THE UNIVERSE. As this sixteenth-century illustration shows, the medieval cosmological view placed the earth at the center of the universe, surrounded by a series of concentric spheres. The earth was imperfect and constantly changing, whereas the heavenly bodies that surrounded it were perfect and incorruptible. Beyond the tenth and final sphere was heaven where God and all the saved souls were located.

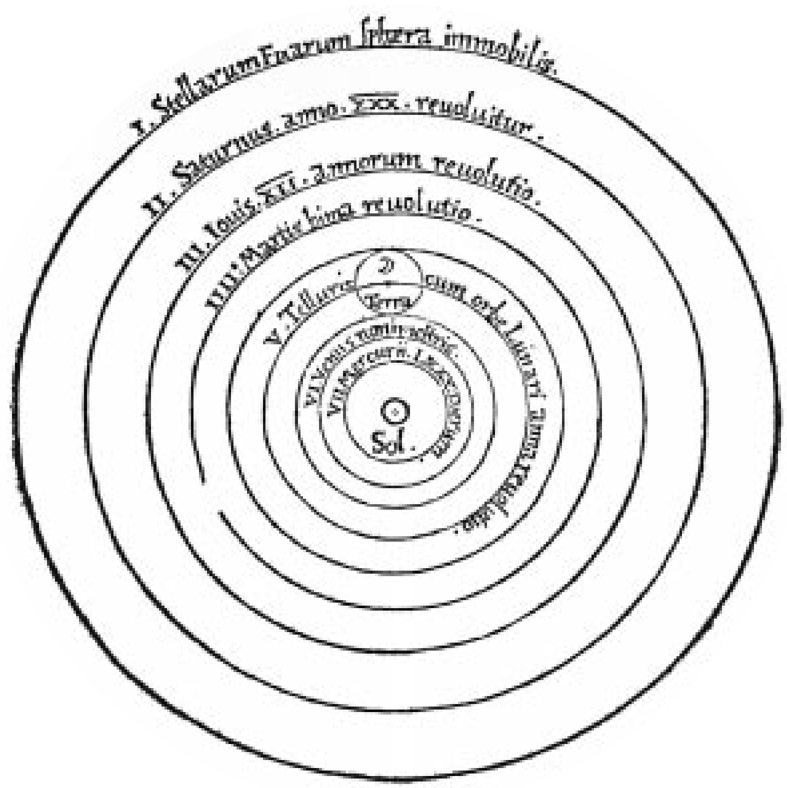
Brahe and Kepler

Copernicus did not have a great impact immediately, however—no revolution occurred overnight. Nevertheless, although most people were not yet ready to accept the theory of Copernicus, doubts about the Ptolemaic system were growing. The next step in destroying the geocentric conception and supporting the Copernican system was taken by Johannes Kepler. It has been argued, however, that Kepler's work would not have occurred without the material provided by Tycho Brahe.

Although Tycho Brahe (1546–1601) advanced a new model of the solar system based on a compromise between Copernicus and Ptolemy—the sun and planets revolved around the earth while the other planets revolved around the sun—his real fame rests on a less spectacular contribution. A Danish nobleman, Brahe was granted possession of an island near Copenhagen by King Frederick II. Here Brahe built the elaborate Uraniborg castle, which he outfitted with a library, observatories, and instruments he had designed for more precise astronomical observations. For twenty years, Brahe patiently concentrated on compiling a detailed record of his observations of the positions and movements of the stars and planets, a series of observations that have been described as the most accurate up to that time. This body of data led him to reject the Aristotelian-Ptolemaic system, but at the same time he was unable to accept Copernicus's suggestion that the earth actually moved. Brahe's last years were spent in Prague as imperial mathematician to Emperor Rudolf II, who took a keen interest in astronomy, astrology, and the Hermetic tradition. While he was in Prague, Brahe took on an assistant by the name of Johannes Kepler.

Johannes Kepler (1571–1630) had been destined by his parents for a career as a Lutheran minister. While studying theology at the university at Tübingen, however, he fell under the influence of Michael Mästlin, Germany's best-known astronomer, and spent much time pursuing his real interests, mathematics and astronomy. He abandoned theology and became a teacher of mathematics and astronomy at Graz in Austria.

Kepler's work illustrates well the narrow line that often separated magic and science in the early Scientific Revolution. An avid astrologer, Kepler possessed a keen interest in Hermetic thought and Neoplatonic mathematical magic. In a book written in 1596, he elaborated upon his theory that the universe was constructed on the basis of geometric figures, such as the pyramid and the cube (see the box on p. 467). Believing that the harmony of the human soul (a divine attribute) was mirrored in the numerical relationships existing between the planets, he focused much of his attention upon discovering the "music of the spheres." Kepler was also a brilliant mathematician and astronomer and, after Brahe's death, succeeded him as imperial mathematician to Rudolf II. There he gained possession of Brahe's detailed astronomical data and, using them, arrived at his three laws of planetary motion. These laws may have confirmed Kepler's interest in the "music



THE COPERNICAN SYSTEM. **The Copernican system was presented in *On the Revolutions of the Heavenly Spheres*, published shortly before Copernicus's death. As shown in this illustration from the first edition of the book, Copernicus maintained that the sun was the center of the universe and that the planets, including the earth, revolved around it. Moreover, the earth rotated daily on its axis.**

On the Revolutions of the Heavenly Spheres

Nicolaus Copernicus began a revolution in astronomy when he argued that it was the sun and not the earth that was at the center of the universe. Expecting controversy and scorn, Copernicus hesitated to publish the work in which he put forth his heliocentric theory. He finally relented, however, and managed to see a copy of it just before he died.

Nicolaus Copernicus, *On the Revolutions of the Heavenly Spheres*

For a long time, then, I reflected on this confusion in the astronomical traditions concerning the derivation of the motions of the universe's spheres. I began to be annoyed that the movements of the world machine, created for our sake by the best and most systematic Artisan of all, were not understood with greater certainty by the philosophers, who otherwise examined so precisely the most insignificant trifles of this world. For this reason I undertook the task of rereading the works of all the philosophers which I could obtain to learn whether anyone had ever proposed other motions of the universe's spheres than those expounded by the teachers of astronomy in the schools. And in fact first I found in Cicero that Hicetas supposed the earth to move. Later I also discovered in Plutarch that certain others were of this opinion. I have decided to set his words down here, so that they may be available to everybody:

> Some think that the earth remains at rest. But Philolaus the Pythagorean believes that, like the sun and moon, it revolves around the fire in an oblique circle. Heraclides of Pontus and Ecphantus the Pythagorean make the earth move, not in a progressive motion, but like a wheel in a rotation from the west to east about its own center.

Therefore, having obtained the opportunity from these sources, I too began to consider the mobility of the earth. And even though the idea seemed absurd, nevertheless I knew that others before me had been granted the freedom to imagine any circles whatever for the purpose of explaining the heavenly phenomena. Hence I thought that I too would be readily permitted to ascertain whether explanations sounder than those of my predecessors could be found for the revolution of the celestial spheres on the assumption of some motion of the earth.

Having thus assumed the motions which I ascribe to the earth later on in the volume, by long and intense study I finally found that if the motions of the other planets are correlated with the orbiting of the earth, and are computed for the revolution of each planet, not only do their phenomena follow therefrom but also the order and size of all the planets and spheres, and heaven itself is so linked together that in no portion of it can anything be shifted without disrupting the remaining parts and the universe as a whole. . . .

Hence I feel no shame in asserting that this whole region engirdled by the moon, and the center of the earth, traverse this grand circle amid the rest of the planets in an annual revolution around the sun. Near the sun is the center of the universe. Moreover, since the sun remains stationary, whatever appears as a motion of the sun is really due rather to the motion of the earth.

of the spheres," but more importantly, they confirmed Copernicus's heliocentric theory while modifying it in some ways. Above all, they drove another nail into the coffin of the Aristotelian-Ptolemaic system.

Kepler published his first two laws of planetary motion in 1609. Although at Tübingen he had accepted Copernicus's heliocentric ideas, in his first law he rejected Copernicus by showing that the orbits of the planets around the sun were not circular but elliptical in shape with the sun at one focus of the ellipse rather than at the center. In his second law, he demonstrated that the speed of a planet is greater when it is closer to the sun and decreases as its distance from the sun increases. This proposition destroyed a fundamental Aristotelian tenet that Copernicus had shared—that the motion of the planets was steady and unchanging. Published ten years later, Kepler's third law established that the square of a planet's period of revolution is proportional to the cube of its average distance from the sun. In other words, planets with larger orbits revolve at a slower average velocity than those with smaller orbits.

Kepler's three laws effectively eliminated the idea of uniform circular motion as well as the idea of crystalline spheres revolving in circular orbits. The basic structure of the traditional Ptolemaic system had been disproved, and people had been freed to think in new terms of the actual paths of planets revolving around the sun in elliptical orbits. By the end of Kepler's life, the Ptolemaic system was rapidly losing ground to the new ideas. Important questions remained unanswered, however: What were the planets made of? And how does one explain motion in the universe? It was an Italian scientist who achieved the next important breakthrough to a new cosmology by answering the first question and making important strides toward answering the second.

Galileo

Galileo Galilei (1564–1642) came from a lesser noble Pisan family. Knowing that his son was obviously gifted, his father encouraged him to study medicine, which at that time was a financially rewarding career. Before long Galileo abandoned medicine for his true love, mathe-

Kepler and the Emerging Scientific Community

The exchange of letters between intellectuals was an important avenue for scientific communication. Through letters, they could provide practical assistance to each other as well as offer encouragement when their innovative work was received negatively. After receiving a copy of Johannes Kepler's first major work, the Italian Galileo Galilei wrote to Kepler, inaugurating a correspondence between them. This selection contains samples of their letters to each other as well as Kepler's letter to his teacher at Tübingen.

❉ Galileo to Kepler, Padua, August 4, 1597

Your book, highly learned gentleman, which you sent me through Paulus Amberger, reached me not days ago but only a few hours ago, and as this Paulus just informed me of his return to Germany, I should think myself indeed ungrateful if I should not express to you my thanks by this letter. I thank you especially for having deemed me worthy of such a proof of your friendship. . . . So far I have read only the introduction, but have learned from it in some measure your intentions and congratulate myself on the good fortune of having found such a man as a companion in the exploration of truth. For it is deplorable that there are so few who seek the truth and do not pursue a wrong method of philosophizing. But this is not the place to mourn about the misery of our century but to rejoice with you about such beautiful ideas proving the truth. . . . I would certainly dare to approach the public with my ways of thinking if there were more people of your mind. As this is not the case, I shall refrain from doing so. . . . I shall always be at your service. Farewell, and do not neglect to give me further good news of yourself.

Yours in sincere friendship,
Galilaeus Galilaeus
Mathematician at the Academy of Padua

❉ Kepler to Michael Mästlin, Graz, September 1597

. . . Lately I have sent two copies of my little book to Italy. They were received with gladness by a mathematician named Galileo Galilei, as he signs himself. He has also been attached for many years to the Copernican heresy.

❉ Kepler to Galileo, Graz, October 13, 1597

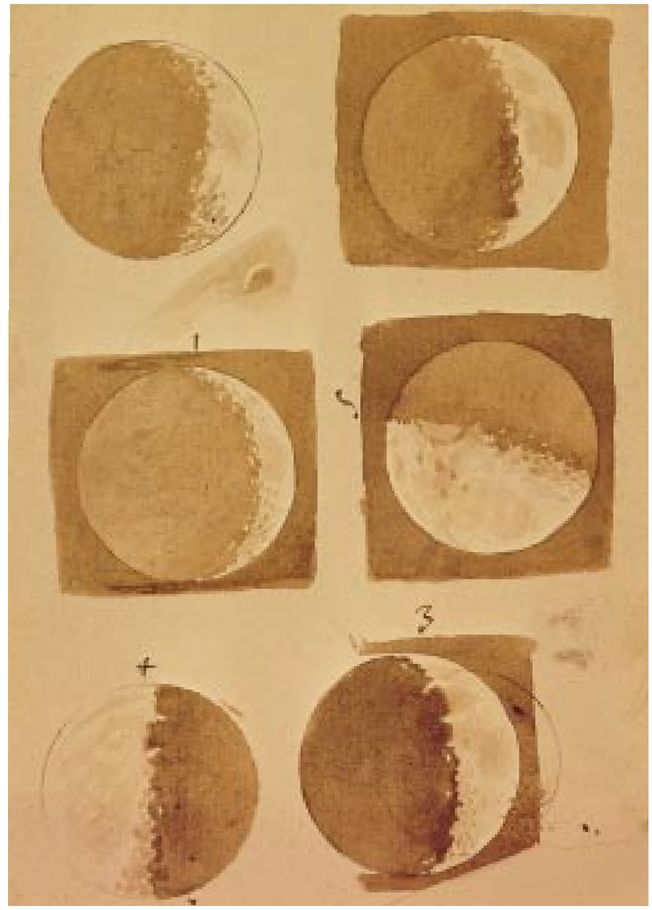
I received your letter of August 4 on September 1. It was a double pleasure to me. First because I became friends with you, the Italian, and second because of the agreement in which we find ourselves concerning Copernican cosmography. As you invite me kindly at the end of your letter to enter into correspondence with you, and I myself feel greatly tempted to do so, I will not let pass the occasion of sending you a letter with the present young nobleman. For I am sure, if your time has allowed it, you have meanwhile obtained a closer knowledge of my book. And so a great desire has taken hold of me, to learn your judgment. For this is my way, to urge all those to whom I have written to express their candid opinion. Believe me, the sharpest criticism of one single understanding man means much more to me than the thoughtless applause of the great masses.

I would, however, have wished that you who have such a keen insight into everything would choose another way to reach your practical aims. By the strength of your personal example you advise us, in a cleverly veiled manner, to go out of the way of general ignorance and warn us against exposing ourselves to the furious attacks of the scholarly crowd. (In this you are following the lead of Plato and Pythagoras, our true masters.) But after the beginning of a tremendous enterprise has been made in our time, and furthered by so many learned mathematicians, and after the statement that the earth moves can no longer be regarded as something new, would it not be better to pull the rolling wagon to its destination with united effort. . . . For it is not only you Italians who do not believe that they move unless they feel it, but we in Germany, too, in no way make ourselves popular with this idea. Yet there are ways in which we protect ourselves against these difficulties. . . . Be of good cheer, Galileo, and appear in public. If I am not mistaken there are only a few among the distinguished mathematicians of Europe who would dissociate themselves from us. So great is the power of truth. If Italy seems less suitable for your publication and if you have to expect difficulties there, perhaps Germany will offer us more freedom. But enough of this. Please let me know, at least privately if you do not want to do so publicly, what you have discovered in favor of Copernicus.

matics, and was soon teaching this subject, first at Pisa and later at Padua, one of the most prestigious universities in Europe.

Galileo was the first European to make systematic observations of the heavens by means of a telescope, thereby inaugurating a new age in astronomy. He had heard of a Flemish lens grinder who had created a "spyglass" that magnified objects seen at a distance and soon constructed his own after reading about it. Instead of peering at terrestrial objects, Galileo turned his telescope to the skies and made a remarkable series of discoveries: mountains and craters on the moon, four moons revolving around Jupiter, the phases of Venus, and sunspots. Galileo's observations seemed to destroy yet another

JOHANNES KEPLER. Abandoning theology in favor of mathematics and astrology, Kepler was a key figure in the rise of the new astronomy. Building upon Tycho Brahe's vast astronomical data, Kepler discovered the three laws of planetary motion that both confirmed and modified the Copernican theory. They also eliminated the Ptolemaic-Aristotelian ideas of uniform circular motion and crystalline spheres moving in circular orbits.



GALILEO'S SKETCH OF THE PHASES OF THE MOON. Galileo Galilei was the first European scientist to use a telescope in making systematic observations of the heavens. Galileo discovered mountains on the moon, sunspots, and the phases of Venus. Shown here are drawings of the moon from Galileo's notes for one of his books.

aspect of the traditional cosmology in that the universe seemed to be composed of material substance similar to that of the earth rather than ethereal or perfect and unchanging substance.

Galileo's revelations, published in *The Starry Messenger* in 1610, stunned his contemporaries and probably did more to make Europeans aware of the new picture of the universe than the mathematical theories of Copernicus and Kepler (see the box on p. 469). The English ambassador in Venice wrote to the chief minister of King James I in 1610:

> I send herewith unto His Majesty the strangest piece of news . . . that he has ever yet received from any part of the world; which is the annexed book of the Mathematical Professor at Padua [Galileo], who by the help of an optical instrument . . . has discovered four new planets rolling about the sphere of Jupiter. . . . So upon the whole subject he has first overthrown all former astronomy. . . . By the next ship your Lordship shall receive from me one of the above instruments [a telescope], as it is bettered by this man.[7]

During a trip to Rome, Galileo was received by cardinals and scholars as a conquering hero. Grand Duke Cosimo II of Florence offered him a new position as his court mathematician, which Galileo readily accepted. But even in the midst of his newfound acclaim, Galileo found himself increasingly suspect by the authorities of the Catholic church.

In *The Starry Messenger,* Galileo had revealed himself as a firm proponent of Copernicus's heliocentric system. Encouraged by the Dominicans, who held strongly to Aristotelian ideas, and the Jesuits, who feared that any dissension would weaken Catholicism in its struggle with Protestantism, the Roman Inquisition (or Holy Office) of the Catholic church condemned Copernicanism and ordered Galileo to reject the Copernican thesis. As one cardinal commented, "the intention of the Holy Spirit is to teach us not how the heavens go, but how to go to heaven." The report of the Inquisition ran: "That the doctrine that the sun was the center of the world and immovable was false and absurd, formally heretical and contrary

The Starry Messenger

The Italian Galileo Galilei was the first European to use a telescope to make systematic observations of the heavens. His observations, as reported in The Starry Messenger *in 1610, stunned European intellectuals by revealing that the celestial bodies were not perfect and immutable, as had been believed, but were apparently composed of material substance similar to the earth. In this selection, Galileo describes how he devised a telescope and what he saw with it.*

❋ Galileo Galilei, *The Starry Messenger*

About ten months ago a report reached my ears that a certain Fleming had constructed a spyglass by means of which visible objects, though very distant from the eye of the observer, were distinctly seen as if nearby. Of this truly remarkable effect several experiences were related, to which some persons gave credence while others denied them. A few days later the report was confirmed to me in a letter from a noble Frenchman at Paris, Jacques Badovere, which caused me to apply myself wholeheartedly to inquire into the means by which I might arrive at the invention of a similar instrument. This I did shortly afterwards, my basis being the theory of refraction. First I prepared a tube of lead, at the ends of which I fitted two glass lenses, both plane on one side while on the other side one was spherically convex and the other concave. Then placing my eye near the concave lens I perceived objects satisfactorily large and near, for they appeared three times closer and nine times larger than when seen with the naked eye alone. Next I constructed another one, more accurate, which represented objects as enlarged more than sixty times. Finally, sparing neither labor nor expense, I succeeded in constructing for myself so excellent an instrument that objects seen by means of it appeared nearly one thousand times larger and over thirty times closer than when regarded without natural vision.

It would be superfluous to enumerate the number and importance of the advantages of such an instrument at sea as well as on land. But forsaking terrestrial observations, I turned to celestial ones, and first I saw the moon from as near at hand as if it were scarcely two terrestrial radii. After that I observed often with wondering delight both the planets and the fixed stars, and since I saw these latter to be very crowded, I began to seek (and eventually found) a method by which I might measure their distances apart. . . .

Now let us review the observations made during the past two months, once more inviting the attention of all who are eager for true philosophy to the first steps of such important contemplations. Let us speak first of that surface of the moon which faces us. For greater clarity I distinguish two parts of this surface, a lighter and a darker; the lighter part seems to surround and to pervade the whole hemisphere, while the darker part discolors the moon's surface like a kind of cloud, and makes it appear covered with spots. . . . From observation of these spots repeated many times I have been led to the opinion and conviction that the surface of the moon is not smooth, uniform, and precisely spherical as a great number of philosophers believe it (and the other heavenly bodies) to be, but is uneven, rough, and full of cavities and prominences, being not unlike the face of the earth, relieved by chains of mountains and deep valleys.

to Scripture, whereas the doctrine that the earth was not the center of the world but moved, and has further a daily motion, was philosophically false and absurd and theologically at least erroneous."[8] Galileo was told, however, that he could continue to discuss Copernicanism as long as he maintained that it was not a fact but a mathematical supposition. It is apparent from the Inquisition's response that the church attacked the Copernican system because it threatened not only Scripture, but also an entire conception of the universe. The heavens were no longer a spiritual world, but a world of matter. Humans were no longer at the center and God was no longer in a specific place. The new system raised such uncertainties that it seemed prudent simply to condemn it.

Galileo, however, never really accepted his condemnation. In 1632, he published his most famous work, *Dialogue on the Two Chief World Systems: Ptolemaic and Copernican*. Unlike most scholarly treatises, it was written in Italian rather than Latin, making it more widely available to the public, which no doubt alarmed the church authorities. The work took the form of a dialogue among Simplicio, a congenial but somewhat stupid supporter of Aristotle and Ptolemy; Sagredo, an open-minded layman; and Salviati, a proponent of Copernicus's ideas. There is no question who wins the argument, and the *Dialogue* was quickly perceived as a defense of the Copernican system. Galileo was dragged once more before the Inquisition in 1633, found guilty of teaching the condemned Copernican system, and forced to recant his errors. Placed under house arrest on his estate near Florence, he spent the remaining eight years of his life studying mechanics, a field in which he made significant contributions.

One of the problems that fell under the heading of mechanics was the principle of motion. The Aristotelian conception, which dominated the late medieval world, held that an object remained at rest unless a force was applied against it. If a force was constantly exerted, then the object moved at a constant rate, but if it was removed, then the object stopped. This conception encountered some difficulties, especially with a projectile thrown out of a cannon. Late medieval theorists had solved this problem by arguing that the rush of air behind the projectile kept it in motion. The Aristotelian principle of motion also raised problems in the new Copernican system. In the Ptolemaic system, the concentric spheres surrounding the earth were weightless, but in the Copernican system, if a constant force had to be applied to objects to cause movement, then what power or force kept the heavy earth and other planets in motion?

Galileo made two contributions to the problem of motion. First, he demonstrated by experiments that if a uniform force was applied to an object, it would move at an accelerated speed rather than a constant speed. Moreover, Galileo discovered the principle of inertia when he argued that a body in motion continues in motion forever unless deflected by an external force. Thus, a state of uniform motion is just as natural as a state of rest. Before Galileo, natural philosophers had tried to explain motion; now their task was to explain changes in motion. Historians agree that Galileo's work on inertia was important, but differ on whether his work was merely the culmination of the medieval tradition or pointed the way to Newton's law of dynamics.

The condemnation of Galileo by the Inquisition seriously hampered further scientific work in Italy, which had been at the forefront of scientific innovation. Leadership in science now passed to the northern countries, especially England, France, and the Dutch Netherlands. By the 1630s and 1640s, no reasonable astronomer could deny that Galileo's discoveries combined with Kepler's mathematical laws had made nonsense of the Ptolemaic-Aristotelian world system and clearly established the reasonableness of the Copernican model. Despite Galileo's theories of dynamics, the problem of explaining motion in the universe and tying together the ideas of Copernicus, Galileo, and Kepler had not yet been done. This would be the work of an Englishman who has long been considered the greatest genius of the Scientific Revolution.

Newton

Born in the little English village of Woolsthorpe in 1642, the young Isaac Newton showed little brilliance until he attended Cambridge University and fell under the influence of the mathematician Isaac Barrow. Newton experienced his first great burst of creative energy in 1666 when the fear of plague closed Cambridge and forced him to return to Woolsthorpe for eighteen months. There Newton discovered his creative talents: "In those days I was in the prime of my life for invention and minded mathematics and philosophy more than at any time since."[9] During this period he invented the calculus, a mathematical means of calculating rates of change, began his investigations into the composition of light, and inaugurated his work on the law of universal gravitation. Two years after his return to Cambridge, in 1669, he accepted a chair of mathematics at the university. During a second intense period of creativity from 1684 to 1686, he wrote his famous *Principia*

ISAAC NEWTON. Pictured here is a portrait of Isaac Newton by Sir Godfrey Kneller. With a single law, that of universal gravitation, Newton was able to explain all motion in the universe. His great synthesis of the work of his predecessors created a new picture of the universe, one in which the universe was viewed as a great machine operating according to natural laws.

(see the box on p. 471). After a nervous breakdown in 1693, he sought and received an administrative post as warden of the royal mint and was advanced to master of the mint by 1699, a post he held until his death in 1727. Made president of the Royal Society (see The Scientific Societies later in this chapter) in 1703 and knighted in 1705 for his great achievements, Sir Isaac Newton wound up the only English scientist to be buried in Westminster Abbey.

Although Isaac Newton occupies a very special place in the history of modern science, we need to remember that he, too, remained extremely interested in aspects of the occult world. He left behind hundreds of manuscript pages of his studies of alchemy, and, in fact, his alchemical experiments were a major feature of his life until he moved to London in 1696 to become warden of the royal mint. The British economist John Maynard Keynes said of Newton after examining his manuscripts in 1936:

> Newton was not the first of the age of reason. He was the last of the magicians. . . . He looked on the whole universe and all that is in it as a riddle, as a secret which could be read by applying pure thought to certain evidence, certain mystic clues which God had laid about the world to allow a sort of philosopher's treasure hunt to the esoteric brotherhood. He believed that these clues were to be found partly in the evidence of the heavens and in the constitution of

Newton's Rules of Reasoning

In 1687, Isaac Newton published his masterpiece, the Mathematical Principles of Natural Philosophy. *In this work, Newton demonstrated the mathematical proofs for his universal law of gravitation and completed the new cosmology begun by Copernicus, Kepler, and Galileo. Newton's work demonstrated that the universe was one huge, regulated, and uniform machine operating according to natural laws. He also described the rules of reasoning by which he arrived at his universal law.*

Isaac Newton, *Rules of Reasoning in Philosophy*

Rule 1

We are to admit no more causes of natural things than such as are both true and sufficient to explain their appearances.

To this purpose the philosophers say that Nature does nothing in vain, and more is in vain when less will serve; for Nature is pleased with simplicity, and affects not the pomp of superfluous causes.

Rule 2

Therefore to the same natural effects we must, as far as possible, assign the same causes.

As to respiration in a man and in a beast; the descent of stones in Europe and in America; the light of our culinary fire and of the sun; the reflection of light in the earth, and in the planets.

Rule 3

The qualities of bodies, which admit neither intensification nor remission of degrees, and which are found to belong to all bodies within the reach of our experiments, are to be esteemed the universal qualities of all bodies whatsoever.

For since qualities of bodies are only known to us by experiments, we are to hold for universal all such as universally agree with experiments; and such as are not liable to diminution can never be quite taken away.

Rule 4

In experimental philosophy we are to look upon propositions inferred by general induction from phenomena as accurately or very nearly true, notwithstanding any contrary hypotheses that may be imagined, till such time as other phenomena occur, by which they may either be made more accurate, or liable to exceptions.

This rule we must follow, that the argument of induction may not be evaded by hypotheses.

> elements, . . . but also partly in certain papers and traditions handed down by the brethren in an unknown chain back to the original cryptic revelation in Babylonia.[10]

Although Newton may have considered himself a representative of the Hermetic tradition, he chose, it has been recently argued, for both political and psychological reasons to repress that part of his being, and it is as the "symbol of Western science" that Newton came to be viewed.

Newton's major work, the "hinge point of modern scientific thought," was his *Mathematical Principles of Natural Philosophy,* known simply as the *Principia* by the first word of its Latin title. In this work, the last, highly influential book in Europe to be written in Latin, Newton spelled out the mathematical proofs demonstrating his universal law of gravitation. Newton's work was the culmination of the theories of Copernicus, Kepler, and Galileo. Though each had undermined some part of the Ptolemaic-Aristotelian cosmology, until Newton no one had pieced together a coherent synthesis for a new cosmology.

In the first book of the *Principia,* Newton defined the basic concepts of mechanics by elaborating the three laws of motion: every object continues in a state of rest or uniform motion in a straight line unless deflected by a force; the rate of change of motion of an object is proportional to the force acting upon it; and to every action there is always an equal and opposite reaction. In Book Three, Newton applied his theories of mechanics to the problems of astronomy by demonstrating that these three laws of motion govern the planetary bodies as well as terrestrial objects. Integral to his whole argument was the universal law of gravitation, which explained why the planetary bodies did not go off in straight lines but continued in elliptical orbits about the sun. In mathematical terms, Newton explained that every object in the universe was attracted to every other object with a force (that is, gravity) that is directly proportional to the product of their masses and inversely proportional to the square of the distances between them.

The implications of Newton's universal law of gravitation were enormous, even though it took another century before they were widely recognized. Newton had demonstrated that one universal law mathematically proved could explain all motion in the universe, from the movements of the planets in the celestial world to an apple falling from a tree in the terrestrial world. The secrets of the natural world could be known by human investigations. At the same time, the Newtonian synthesis created a new cosmology in which the world was seen largely in mechanistic terms. The universe was one huge, regulated,

CHRONOLOGY

Important Works of the Scientific Revolution

Copernicus, *On the Revolutions of the Heavenly Spheres*	1543
Vesalius, *On the Fabric of the Human Body*	1543
Galileo, *The Starry Messenger*	1610
Harvey, *On the Motion of the Heart and Blood*	1628
Galileo, *Dialogue on the Two Chief World Systems*	1632
Cavendish, *Grounds of Natural Philosophy*	1668
Newton, *Principia*	1687

and uniform machine that operated according to natural laws in absolute time, space, and motion. Although Newton believed that God was "everywhere present" and acted as the force that moved all bodies on the basis of the laws he had discovered, later generations dropped his spiritual assumptions. Newton's world-machine, conceived as operating absolutely in time, space, and motion, dominated the Western worldview until the twentieth century, when the Einsteinian revolution based on a concept of relativity superseded the Newtonian mechanistic concept.

Newton's ideas were soon accepted in England, possibly out of national pride and conviction and, as has been argued recently, for political reasons (see Science and Society later in this chapter). Natural philosophers on the continent resisted Newton's ideas, and it took much of the eighteenth century before they were generally accepted everywhere in Europe. They were also reinforced by developments in other fields, especially medicine.

◆ Advances in Medicine

Although the Scientific Revolution of the sixteenth and seventeenth centuries is associated primarily with the dramatic changes in astronomy and mechanics that precipitated a new perception of the universe, a third field that had been dominated by Greek thought in the Late Middle Ages, that of medicine, also experienced a transformation. Late medieval medicine was dominated not by the teachings of Aristotle, but by those of the Greek physician Galen who had lived in the second century A.D.

Galen's influence on the medieval medical world was pervasive in anatomy, physiology, and disease. Galen had relied on animal, rather than human, dissection to arrive at a picture of human anatomy that was quite inaccurate in many instances. Even when Europeans began to practice human dissection in the Late Middle Ages, instruction in anatomy still relied on Galen. While a professor read a text of Galen, an assistant dissected a cadaver for illustrative purposes. Physiology, or the functioning of the body, was also dominated by Galenic hypotheses, including the belief that there were two separate blood systems. One controlled muscular activities and contained bright red blood moving upward and downward through the arteries; the other governed the digestive functions and contained dark red blood that ebbed and flowed in the veins.

Treatment of disease was highly influenced by Galen's doctrine of four bodily humors: blood, considered warm and moist; yellow bile, warm and dry; phlegm, cold and moist; and black bile, cold and dry. Since disease was supposedly the result of an imbalance of humors that could be discerned from the quantity and color of urine, the examination of a patient's urine became the chief diagnostic tool. Although purging and bleeding to remedy the imbalance were often harmful to patients, treatment with traditional herbal medicines sometimes proved beneficial.

Three figures are associated with the changes in medicine in the sixteenth and seventeenth centuries: Paracelsus, Andreas Vesalius, and William Harvey. Philippus Aureolus von Hohenheim (1493–1541), who renamed himself Paracelsus (or greater than Celsus, the ancient physician), was born in a small town near Zürich, the son of a country physician who dabbled in astrology. After leaving home at the age of fourteen, Paracelsus traveled widely and may have been awarded a medical degree from the University of Ferrara. He achieved a moment of glory when he was appointed city physician and professor of medicine at Basel in 1527. But this, like so many other appointments, proved short-lived due to his vanity, cantankerous nature, and quick temper. He could never disguise his contempt for universities and physicians who did not agree with his new ideas:

> I am *monarcha medicorum,* monarch of physicians, and I can prove to you what you cannot prove. . . . It was not the constellations that made me a physician: God made me . . . I need not don a coat of mail or a buckler against you, for you are not learned or experienced enough to refute even one word of mine. I wish I could protect my bald head against the flies as effectively as I can defend my monarchy. . . . Let me tell you this: every little hair on my neck knows more than you and all your scribes, and my shoebuckles are more learned than your Galen and Avicenna, and my beard has more experience than all your high colleges.[11]

Paracelsus was not easy to get along with, and he was forced to wander from one town to another until his death in 1541.

Paracelsus rejected the work of both Aristotle and Galen and attacked the universities as centers of their moribund philosophy. He and his followers hoped to replace the traditional system with a new chemical philosophy that was based upon a new understanding of nature derived from fresh observation and experiment. This chemical philosophy was, in turn, closely connected to a view of the universe based on the macrocosm-microcosm analogy. According to this view, a human being was a small replica (microcosm) of the larger world (macrocosm) about him. All parts of the universe were represented within each person. As Paracelsus said: "For the sun and the moon and all planets, as well as the stars and the whole chaos, are in man. . . . For what is outside is also inside; and what is not outside man is not inside. The outer and the inner are one thing."[12] In accordance with the macrocosmic-microcosmic principle, Paracelsus believed that the chemical reactions of the universe as a whole were reproduced in human beings on a smaller scale. Disease, then, was not caused by an imbalance of the four humors (as Galen had argued), but was due to chemical imbalances that were localized in specific organs and could be treated by chemical remedies.

Although others had used chemical remedies, Paracelsus and his followers differed from them in giving careful attention to the proper dosage of their chemically prepared metals and minerals. Gauging the proper amount was especially important because Paracelsus had turned against the Galenic principle that "contraries cure" in favor of the ancient Germanic folk principle that "like cures like." The poison that caused a disease would be its cure if used in proper form and quantity. This use of toxic substances to cure patients was, despite its apparent effectiveness (Paracelsus did have a strong reputation for actually curing his patients), viewed by Paracelsus's opponents as the practice of a "homicide Physician." Later generations came to view Paracelsus more favorably, and historians who have stressed Paracelsus's concept of disease and recognition of "new drugs" for medicine have viewed him as a father of modern medicine. Others have argued that his macrocosmic-microcosmic philosophy and use of "like cures like" drugs make him the forerunner of both homeopathy and the holistic medicine of the postmodern era.

Historians usually associate the name of Paracelsus with the diagnosis and treatment of disease. The new anatomy of the sixteenth century, however, was the work of Andreas Vesalius (1514–1564). His study of medicine at Paris involved him in the works of Galen, the great ancient authority. Especially important to him was a recently discovered text of Galen, *On Anatomical Procedures,* that led Vesalius to emphasize practical research as the principal avenue for understanding human anatomy. After receiving a doctorate in medicine at the University of Padua in 1536, he accepted a position there as professor of surgery. In 1543, he published his masterpiece, *On the Fabric of the Human Body.*

This book was based on his Paduan lectures, in which he deviated from traditional practice by personally dissecting a body to illustrate what he was discussing. Vesalius's anatomical treatise presented a careful examination of the individual organs and general structure of the human body. The book would not have been feasible without both the artistic advances of the Renaissance and technical developments in the art of printing. Together, they made possible the creation of illustrations superior to any hitherto produced.

Vesalius's "hands-on" approach to teaching anatomy enabled him to overthrow some of Galen's most glaring errors. He did not hesitate, for example, to correct Galen's assertion that the great blood vessels originated from the liver since his own observations made it apparent that they came from the heart. Nevertheless, Vesalius still clung to a number of Galen's erroneous assertions, including the Greek physician's ideas on the ebb and flow of two kinds of blood in the veins and arteries. It was not until William Harvey's work on the circulation of the blood that this Galenic misperception was corrected.

William Harvey (1578–1657) attended Cambridge University and later Padua where he received a doctorate of medicine in 1602. Appointed physician to St. Bartholomew's Hospital in 1609, he later became physician to King James I and Charles I. His reputation, however, rests upon his book, *On the Motion of the Heart and Blood,* published in 1628.

Although questions had been raised in the sixteenth century about Galen's physiological principles, no major break from his system had occurred. Harvey's work, which was based upon meticulous observations and experiments, led him to demolish the ancient Greek's work. Harvey demonstrated that the heart and not the liver was the beginning point of the circulation of blood in the body, that the same blood flows in both veins and arteries, and, most importantly, that the blood makes a complete circuit as it passes through the body. Although Harvey's work dealt a severe blow to Galen's theories, his ideas did not begin to achieve general recognition until the 1660s, when the capillaries, which explained how the body's blood passed from the arteries to the veins, were discovered. Harvey's theory of the circulation of the blood laid the foundation for modern physiology.

Women in the Origins of Modern Science

During the Middle Ages, except for members of religious orders, women who sought a life of learning were severely hampered by the traditional attitude that a woman's proper role was as a daughter, wife, and mother. But in the late fourteenth and early fifteenth centuries, new opportunities for elite women emerged as enthusiasm for the new secular learning called humanism encouraged Europe's privileged and learned men to encourage women to read and study classical and Christian texts. The daughters and sisters of prominent Christian humanists, for example, were known for their learning. In northern Italy, a number of educated families allowed their young women to pursue a life of scholarship. The ideal of a humanist education for some of the daughters of Europe's elite persisted into the seventeenth century, but only for some privileged women.

In the same fashion as they were drawn to humanism, women were also attracted to the Scientific Revolution. Unlike females educated formally in humanist schools, women attracted to science had to obtain a largely informal education. Female contributions to science were

MARGARET CAVENDISH. Shown in this portrait is Margaret Cavendish, the duchess of Newcastle. Her husband, who was thirty years older, encouraged her to pursue her literary interests. In addition to scientific works, she wrote plays, an autobiography, and a biography of her husband entitled *The Life of the Thrice Noble, High and Puissant Prince William Cavendish, Duke, Marquess and Earl of Newcastle.* The autobiography and biography led one male literary critic to call her "a mad, conceited and ridiculous woman."

even more remarkable when we consider that women were largely excluded from universities and the new scientific societies. This was not quite the handicap that it would be today, however. Since science in the seventeenth century was not the preserve of universities, there was often no real dividing line between popular science and professional science, creating chances for women to enter scientific circles. Opportunities for women as well as alternatives to formal humanistic education could often be found in aristocratic and princely courts and in artisan workshops.

European nobles had the leisure and resources that gave them easy access to the world of learning. This door was also open to noblewomen who could participate in the informal scientific networks of their fathers and brothers. One of the most prominent female scientists of the seventeenth century, Margaret Cavendish (1623–1673), came from an aristocratic background. Cavendish was not a popularizer of science for women but a participant in the crucial scientific debates of her time. She also corresponded with important people on these issues. Despite her achievements, however, she was excluded from membership in the Royal Society (see The Scientific Societies later in this chapter), although she was once allowed to attend a meeting. She wrote a number of works on scientific matters including *Observations upon Experimental Philosophy* and *Grounds of Natural Philosophy.* In these works she did not hesitate to attack what she considered the defects of the rationalist and empiricist approaches to scientific knowledge and was especially critical of the growing belief that through science humans would be masters of nature: "We have no power at all over natural causes and effects. . . . for man is but a small part, . . . his powers are but particular actions of Nature, and he cannot have a supreme and absolute power."[13]

As an aristocrat, Margaret Cavendish was a good example of the women in France and England who worked in science. In Germany, women interested in science came from a different background. There the tradition of female participation in craft production enabled some women to become involved in observational science, especially entomology and astronomy. Between 1650 and 1710, 14 percent of all German astronomers were women.

A good example of female involvement in the Scientific Revolution stemming from the craft tradition was Maria Sibylla Merian (1647–1717), who had established a reputation as an important entomologist by the beginning of the eighteenth century. Merian's training came from working in her father's workshop where she learned the art of illustration, a training of great importance since her exact observation of insects and plants was only demonstrated through the superb illustrations she made. Her first work was the *Wonderful Metamorphosis and Special Nourishment of Caterpillars,* an illustrated study of caterpillars showing every stage in their development, which she had carefully observed and rendered in her drawings. In 1699, she undertook an expedition into the wilds of the Dutch colony of Surinam to collect and draw samples of plants and insect life. This led to her major scientific work, the *Metamorphosis of the Insects of Surinam,* in which she used sixty illustrations to show the reproductive and developmental cycles of Surinam's insect life.

The craft organization of astronomy also gave women opportunities to become involved in science. Those who did worked in family observatories; hence, daughters and wives received training as apprentices to fathers or husbands. The most famous of the female astronomers in Germany was Maria Winkelmann (1670–1720). She was educated by her father and uncle and received advanced training in astronomy from a nearby self-taught astronomer. Her opportunity to be a practicing astronomer came when she married Gottfried Kirch, Germany's foremost astronomer. She became his assistant at the astronomical observatory operated in Berlin by the Academy of Science. She made some original contributions, including a hitherto undiscovered comet, as her husband related:

> Early in the morning (about 2:00 A.M.) the sky was clear and starry. Some nights before, I had observed a variable star, and my wife (as I slept) wanted to find and see it for

herself. In so doing, she found a comet in the sky. At which time she woke me, and I found that it was indeed a comet . . . I was surprised that I had not seen it the night before.[14]

Moreover, Winkelmann corresponded with the famous scientist Gottfried Leibniz (who invented the calculus independently of Newton), who praised her effusively as "a most learned woman who could pass as a rarity." When her husband died in 1710, she applied for a position as assistant astronomer for which she was highly qualified. As a woman—with no university degree—she was denied the post by the Berlin Academy, which feared that it would establish a precedent by hiring a woman ("mouths would gape"). Winkelmann managed, nevertheless, to continue her astronomical work a while longer at the private observatory of Baron Friederich von Krosigk in Berlin.

Winkelmann's difficulties with the Berlin Academy reflect the obstacles women faced in being accepted in scientific work, which was considered a male preserve. Although no formal statutes excluded women from membership in the new scientific societies, no woman was invited to join either the Royal Society of England or the French Academy of Sciences until the twentieth century. All of these women scientists were exceptional women since a life devoted to any kind of scholarship was still viewed as being at odds with the domestic duties women were expected to perform.

The nature and value of women had been the subject of an ongoing, centuries-long debate known as the *querelles des femmes*—arguments about women. Male opinions in the debate were largely a carryover from medieval times and were not favorable. Women were portrayed as inherently base, prone to vice, easily swayed, and "sexually insatiable." Hence, men needed to control them. Learned women were viewed as having overcome female liabilities to become like men. One man in praise of a woman scholar remarked that her writings were so good that you "would hardly believe they were done by a woman at all."

In the early modern era, women joined this debate by arguing against these male images of women. They argued that women also had rational minds and could grow from education. Further, since most women were pious, chaste, and temperate, there was no need for male authority over them. These female defenders of women in the *querelles des femmes* emphasized education as the key to women's ability to move into the world. How, then, did the era of the Scientific Revolution affect this debate over the nature of women? As an era of intellectual revolution in which traditional authorities were being overthrown, we might expect significant change in men's views of women. But by and large, instead of becoming an instrument for liberation, science was used to find new support for the old, traditional views about a woman's place in the scheme of things. This was done in a variety of ways.

One approach is evident in the work of William Harvey who was renowned for his work on the circulation of the blood. In his 1651 book on human reproduction, he argued that a woman provided "matter" but it was the man who gave it life and form from his semen. Harvey regarded semen as the active agent, and in his view it was so powerful that it was "vivifying, endowed with force and spirit and generative influence." By the end of the century, however, some scientists were arguing that males and females influenced the generative process equally. Likewise, new views on anatomy also appeared, but interestingly enough were used to perpetuate old stereotypes about women.

From the work of Galen until late in the sixteenth century, the male and female genitals had been portrayed as not significantly different. The uterus, for example, had been pictured as an internal and inadequate penis. According to Galen, "All parts that men have, women have too . . . the difference between them lies in only one thing . . . that in women the parts are within the body, whereas in men they are outside."[15] But this perspective was radically reevaluated in the seventeenth century, and the uterus was now presented as a perfect instrument for childbearing. It was not long before this view was used to reinforce the traditional argument that women were designed for their role as bearer of their husband's children.

An important project in the new anatomy of the sixteenth and seventeenth centuries was the attempt to illustrate the human body and skeleton. For Vesalius, the portrayal of physical differences between males and females was limited to external bodily form (the outlines of the body) and the sexual organs. Vesalius saw no difference in skeletons and portrayed them as the same for men and women. It was not until the eighteenth century, in fact, that a new anatomy finally prevailed. Drawings of female skeletons between 1730 and 1790 varied, but females tended to have a larger pelvic area, and, in some instances, female skulls were portrayed as smaller than those of males. Eighteenth-century studies on the anatomy and physiology of sexual differences provided "scientific evidence" to reaffirm the traditional inferiority of women. The larger pelvic area "proved" that women were meant to be childbearers whereas the larger skull "demonstrated" the superiority of the male mind. Male-dominated science had been used to "prove" male social dominance.

At the same time, during the seventeenth and eighteenth centuries, women even lost the traditional spheres of influence they had possessed, especially in the science-related art of midwifery. Women serving as midwives had traditionally been responsible for birthing. Similar to barber-surgeons or apothecaries (see Chapter 17), midwives had acquired their skills through apprenticeship. But the impact of the Scientific Revolution caused traditional crafts to be upgraded and then even professionalized as males took over. When medical men entered this arena, they also began to use devices and techniques derived from the study of anatomy. These were increasingly used to justify the male takeover of the traditional role of midwives. By the end of the eighteenth century, midwives were simply accessories to the art they had once controlled, except for the poor. Since little money was to be made in

The "Natural" Inferiority of Women

Despite the shattering of old views and the emergence of a new worldview in the Scientific Revolution of the seventeenth century, attitudes toward women remained tied to traditional perspectives. In this selection, the philosopher Benedict de Spinoza argues for the "natural" inferiority of women to men.

Benedict de Spinoza, *A Political Treatise*

But, perhaps, someone will ask, whether women are under men's authority by nature or institution? For if it has been by mere institution, then we had no reason compelling us to exclude women from government. But if we consult experience itself, we shall find that the origin of it is in their weakness. For there has never been a case of men and women reigning together, but wherever on the earth men are found, there we see that men rule, and women are ruled, and that on this plan, both sexes live in harmony. But on the other hand, the Amazons, who are reported to have held rule of old, did not suffer men to stop in their country, but reared only their female children, killing males to whom they gave birth. But if by nature women were equal to men, and were equally distinguished by force of character and ability, in which human power and therefore human right chiefly consist; surely among nations so many and different some would be found, where both sexes rule alike, and others, where men are ruled by women, and so brought up, that they can make less use of their abilities. And since this is nowhere the case, one may assert with perfect propriety, that women have not by nature equal right with men: but that they necessarily give way to men, and that thus it cannot happen, that both sexes should rule alike, much less that men should be ruled by women. But if we further reflect upon human passions, how men, in fact, generally love women merely from the passion of lust, and esteem their cleverness and wisdom in proportion to the excellence of their beauty, and also how very ill-disposed men are to suffer the women they love to show any sort of favor to others, and other facts of this kind, we shall easily see that men and women cannot rule alike without great hurt to peace.

serving them, midwives were allowed to continue to practice their traditional art for the lower classes.

Overall the Scientific Revolution reaffirmed traditional ideas about women's nature. Male scientists used the new science to spread the view that women were inferior by nature, subordinate to men, and suited by nature to play a domestic role as nurturing mothers. The widespread distribution of books ensured the continuation of these ideas (see the box above). Jean de La Bruyère, the seventeenth-century French moralist, was typical when he remarked that an educated woman was like a gun that was a collector's item "which one shows to the curious, but which has no use at all, any more than a carousel horse."[16]

Toward a New Earth: Descartes, Rationalism, and a New View of Humankind

The fundamentally new conception of the universe contained in the cosmological revolution of the sixteenth and seventeenth centuries inevitably had an impact on the Western view of humankind. Nowhere is this more evident than in the work of René Descartes (1596–1650), an extremely important figure in Western history. Descartes began by reflecting the doubt and uncertainty that seemed pervasive in the confusion of the seventeenth century and ended with a philosophy that dominated Western thought until the twentieth century.

René Descartes was born into a family of the French lower nobility. After a Jesuit education, he studied law at Poitiers but traveled to Paris to study by himself. As far as can be deduced, he spent much of this period absorbed in the skeptical works of Montaigne. In 1618, at the beginning of the Thirty Years' War, Descartes volunteered for service in the army of Maurice of Nassau, but his motives seem to have been guided less by the desire for military action than for travel and leisure time to think. On the night of November 10, 1619, Descartes underwent what one historian has called an experience comparable to the "ecstatic illumination of the mystic." Having perceived in one night the outlines of a new rational-mathematical system, with a sense of divine approval he made a new commitment to mind, mathematics, and a mechanical universe. For the rest of his life, Descartes worked out the details of his vision.

The starting point for Descartes's new system was doubt, as he explained at the beginning of his most famous work, *Discourse on Method,* written in 1637:

> From my childhood I have been familiar with letters; and as I was given to believe that by their means a clear and assured knowledge can be acquired of all that is useful in life, I was extremely eager for instruction in them. As soon, however, as I had completed the course of study, at the close of which it is customary to be admitted into the order of the learned, I entirely changed my opinion. For I found myself entangled in so many doubts and errors that, as it seemed to me, the endeavor to instruct myself had served only to disclose to me more and more of my ignorance.[17]

DESCARTES WITH QUEEN CHRISTINA OF SWEDEN. René Descartes was one of the primary figures in the Scientific Revolution. Claiming to use reason as his sole guide to truth, Descartes posited a sharp distinction between mind and matter. He is shown here, standing to the right of Queen Christina of Sweden. The queen had a deep interest in philosophy and invited Descartes to her court.

Descartes decided to set aside all that he had learned and begin again. Having rejected the senses, because they are easily deceived, one fact seemed to Descartes beyond doubt—his own existence:

> But I immediately became aware that while I was thus disposed to think that all was false, it was absolutely necessary that I who thus thought should be something; and noting that this truth *I think, therefore I am,* was so steadfast and so assured that the suppositions of the skeptics, to whatever extreme they might all be carried, could not avail to shake it, I concluded that I might without scruple accept it as being the first principle of the philosophy I was seeking.[18]

With this emphasis on the mind, Descartes asserted that he would accept only those things that his reason said were true.

From his first postulate, Descartes deduced two additional principles, the existence of God and the separation of mind and matter. Since he—an imperfect being—had conceived of the idea of perfection, it could only have come from a perfect being, that is, God:

> And since it is no less contradictory that the more perfect should result from, and depend on, the less perfect than that something should proceed from nothing, it is equally impossible I should receive it from myself. Thus we are committed to the conclusion that it has been placed in me by a nature which is veritably more perfect than I am, and which has indeed within itself all the perfections of which I have any idea, that is to say, in a single word, that is God.[19]

Secondly, Descartes argued that since "the mind cannot be doubted but the body and material world can, the two must be radically different." From this came an absolute dualism between mind and body, or what has also been called Cartesian dualism.

According to Descartes, the universe contains two things, both of which God has created. One is thinking substance, what we call the mind. It is essentially spiritual and not composed of matter. Everything in the universe except the thinking substance or mind is extended substance, what we call matter. Using mind or human reason, the path to certain knowledge, and its best instrument, mathematics, humans can understand the material world because it is pure mechanism, a machine that is governed by its own physical laws because it was created by God—the great geometrician.

Descartes's conclusions about the nature of the universe and human beings had important implications. His separation of mind and matter allowed scientists to view matter as dead or inert, as something that was totally separate from themselves and could be investigated independently by reason. The split between mind and body led Westerners to equate their identity with mind and reason rather than with the whole organism. Descartes has rightly been called the father of modern rationalism (see the box on p. 478). His books were placed on the papal Index of Forbidden Books and condemned by many Protestant theologians. The radical Cartesian split between mind and matter, and between mind and body, had devastating implications not only for traditional religious views of the universe, but for how Westerners viewed themselves.

◆ The Scientific Method

In the course of the Scientific Revolution, attention was also paid to the problem of establishing the proper means to examine and understand the physical realm. This development of a scientific method was crucial to the evolution of science in the modern world.

Curiously enough, it was an Englishman with few scientific credentials who attempted to put forth a new method of acquiring knowledge that made an impact on the Royal Society in England in the seventeenth century and other European scientists in the eighteenth century. Francis Bacon (1561–1626), a lawyer and lord chancellor, rejected Copernicus and Kepler and misunderstood Galileo. And yet in his unfinished work, *The Great Instauration (The Great Restoration)*, he called for his contemporaries "to commence a total reconstruction of sciences, arts, and all human knowledge, raised upon the proper foundations." Bacon did not doubt humans' ability to

The Father of Modern Rationalism

René Descartes has long been viewed as the founder of modern rationalism and modern philosophy because he believed that human beings could understand the world—itself a mechanical system—by the same rational principles inherent in mathematical thinking. In his Discourse on Method, *he elaborated upon his approach to discovering truth.*

René Descartes, *Discourse on Method*

In place of the numerous precepts which have gone to constitute logic, I came to believe that the four following rules would be found sufficient, always provided I took the firm and unswerving resolve never in a single instance to fail in observing them.

The first was to accept nothing as true which I did not evidently know to be such, that is to say, scrupulously to avoid precipitance and prejudice, and in the judgments I passed to include nothing additional to what had presented itself to my mind so clearly and so distinctly that I could have no occasion for doubting it.

The second, to divide each of the difficulties I examined into as many parts as may be required for its adequate solution.

The third, to arrange my thoughts in order, beginning with things the simplest and easiest to know, so that I may then ascend little by little, as it were step by step, to the knowledge of the more complex, and in doing so, to assign an order of thought even to those objects which are not of themselves in any such order of precedence.

And the last, in all cases to make enumerations so complete, and reviews so general, that I should be assured of omitting nothing.

Those long chains of reasonings, each step simple and easy, which geometers are wont to employ in arriving even at the most difficult of their demonstrations, have led me to surmise that all the things we human beings are competent to know are interconnected in the same manner, and that none are so remote as to be beyond our reach or so hidden that we cannot discover them—that is, provided we abstain from accepting as true what is not thus related, i.e., keep always to the order required for their deduction one from another. And I had no great difficulty in determining what the objects are with which I should begin, for that I already knew, namely, that it was with the simplest and easiest. Bearing in mind, too, that of all those who in time past have sought for truth in the sciences, the mathematicians alone have been able to find any demonstrations, that is to say, any reasons which are certain and evident, I had no doubt that it must have been by a procedure of this kind that they had obtained them.

know the natural world, but he believed that they had proceeded incorrectly: "The entire fabric of human reason which we employ in the inquisition of nature is badly put together and built up, and like some magnificent structure without foundation."

Bacon's new foundation—a correct scientific method—was to be built upon inductive principles. Rather than beginning with assumed first principles from which logical conclusions could be deduced, he urged scientists to proceed from the particular to the general. From carefully organized experiments and thorough, systematic observations, correct generalizations could be developed.

Bacon was clear about what he believed his method could accomplish. His concern was more for practical than for pure science. He stated that "the true and lawful goal of the sciences is none other than this: that human life be endowed with new discoveries and power." He wanted science to contribute to the "mechanical arts" by creating devices that would benefit industry, agriculture, and trade. Bacon was prophetic when he said that "I am laboring to lay the foundation, not of any sect or doctrine, but of human utility and power." And how would this "human power" be used? To "conquer nature in action."[20] The control and domination of nature became a central proposition of modern science and the technology that accompanied it. Only in the twentieth century did some scientists begin to ask whether this assumption might not be at the heart of the earth's ecological crisis.

René Descartes proposed a different approach to scientific methodology by emphasizing deduction and mathematical logic. As Descartes explained in *Discourse on Method,* each step in an argument should be as sharp and well founded as a mathematical proof:

> These long chains of reasonings which geometers are accustomed to using to reach their most difficult demonstrations, had given me cause to imagine that everything which can be encompassed by man's knowledge is linked in the same way, and that provided only that one abstains from accepting any for true which is not true, and that one always keeps the right order for one thing to be deduced from that which precedes it, there can be nothing so distant that one does not reach it eventually, or so hidden that one cannot discover it.[21]

Descartes believed then that one could start with self-evident truths, comparable to geometrical axioms, and deduce more complex conclusions. His emphasis on deduction and mathematical order complemented Bacon's stress on experiment and induction. It was Sir Isaac Newton who synthesized them into a single scientific methodology by uniting Bacon's empiricism with Descartes's rationalism. This scientific method began with systematic observations and experiments, which were used to arrive at general concepts. New deductions derived from these general concepts could then be tested and verified by precise experiments.

The scientific method, of course, was valuable in answering the question "how" something works, and its success in doing this gave others much confidence in the method. It did not attempt to deal with the question of "why" something happens or the purpose and meaning behind the world of nature. This allowed religion still to be important in the seventeenth century.

◆ Science and Religion in the Seventeenth Century

In Galileo's struggle with the inquisitorial Holy Office of the Catholic church, we see the beginning of the conflict between science and religion that has marked the history of modern Western civilization. Since time immemorial, theology had seemed to be the queen of the sciences. It was natural that the churches would continue to believe that religion was the final measure of all things. To the emerging scientists, however, it often seemed that theologians knew not of what they spoke. These "natural philosophers" then tried to draw lines between the knowledge of religion and the knowledge of "natural philosophy" or nature. Galileo had clearly felt that it was unnecessary to pit science against religion:

> In discussions of physical problems we ought to begin not from the authority of scriptural passages, but from sense-experiences and necessary demonstrations; for the holy Bible and the phenomena of nature proceed alike from the divine word, the former as the dictate of the Holy Ghost and the latter as the observant executrix of God's commands. It is necessary for the Bible, in order to be accommodated to the understanding of every man, to speak many things which appear to differ from the absolute truth so far as the bare meaning of the words is concerned. But Nature, on the other hand, is inexorable and immutable; she never transgresses the laws imposed upon her, or cares a whit whether her abstruse reasons and methods of operation are understandable to men.[22]

To Galileo it made little sense for the church to determine the nature of physical reality on the basis of biblical texts that were subject to radically divergent interpretations. The church, however, decided otherwise in Galileo's case and lent its great authority to one scientific theory, the Ptolemaic-Aristotelian cosmology, no doubt because it fit so well with its own philosophical views of reality. But the church's decision had tremendous consequences, just as the rejection of Darwin's ideas did in the nineteenth century. For educated individuals, it established a dichotomy between scientific investigations and religious beliefs. As the scientific beliefs triumphed, it became almost inevitable that religious beliefs would suffer, leading to a growing secularization in European intellectual life, precisely what the church had hoped to combat by opposing Copernicanism. Many seventeenth-century intellectuals were both religious and scientific and believed that the implications of this split would be tragic. Some believed that the split was largely unnecessary while others felt the need to combine God, humans, and a mechanistic universe into a new philosophical synthesis. Two individuals—Spinoza and Pascal—illustrate some of the wide diversity in the response of European intellectuals to the implications of the cosmological revolution of the seventeenth century.

Benedict de Spinoza (1632–1677) was a philosopher who grew up in the relatively tolerant atmosphere of Amsterdam. He was excommunicated from the Amsterdam synagogue at the age of twenty-four for rejecting the tenets of Judaism. Ostracized by the local Jewish community and major Christian churches alike, Spinoza lived a quiet, independent life, earning a living by grinding optical lenses and refusing to accept an academic position in philosophy at the University of Heidelberg for fear of compromising his freedom of thought. Spinoza read a great deal of the new scientific literature and was influenced by Descartes.

Although he followed Descartes's rational approach to knowledge, Spinoza was unwilling to accept the implications of Descartes's ideas, especially the separation of mind and matter and the apparent separation of an infinite God from the finite world of matter. God was not simply creator of the universe, he was the universe. All that is is in God, and nothing can be apart from God. This philosophy of pantheism (others have labeled it panentheism or monism) was set out in Spinoza's book, *Ethics Demonstrated in the Geometrical Manner,* which was not published until after his death.

To Spinoza, human beings are not "situated in nature as a kingdom within a kingdom," but are as much a part of God or nature or the universal order as other natural objects. The failure to understand God had led to many misconceptions; for one, that nature exists only for one's use:

> As they find in themselves and outside themselves many means which assist them not a little in their search for what is useful, for instance, eyes for seeing, teeth for chewing, herbs and animals for yielding food, the sun for giving light, the sea for breeding fish, they come to look on the whole of nature as a means for obtaining such conveniences.[23]

Furthermore, unable to find any other cause for the existence of these things, they attributed them to a creator-God who must be worshiped to gain their ends: "Hence also it follows, that everyone thought out for himself, according to his abilities, a different way of worshiping God, so that God might love him more than his fellows, and direct the whole course of nature for the satisfaction of his blind cupidity and insatiable avarice." Then, when nature appeared unfriendly in the form of storms, earthquakes, and diseases, "they declared that such things happen, because the gods are angry at some wrong done them by men, or at some fault committed in their worship," rather than realizing "that good and evil fortunes fall to the lot of pious and impious alike."[24] Likewise, human beings made moral condemnations of others because they failed to understand that human emotions, "passions of hatred, anger, envy and so, considered in themselves, follow from the same necessity and efficacy of nature" and "nothing comes to pass in nature in contravention to her universal laws." To explain human emotions, like everything else, we need to analyze them as we would the movements of planets: "I shall, therefore, treat of the nature and strength of my emotions according to the same method as I employed heretofore in my investigations concerning God and the mind. I shall consider human actions and desires in exactly the same manner as though I were concerned with lines, planes, and solids."[25] Everything has a rational explanation and humans are capable of finding it. In using reason, people can find true happiness. Their real freedom comes when they understand the order and necessity of nature and achieve detachment from passing interests.

Spinoza's complex synthesis of God, humans, and the universe was not easily accepted by his contemporaries, and his pantheism was mistakenly condemned as "hideous atheism." Others were upset by his attitude toward morality because he viewed it as found in nature and known by reason, not revealed to people through the Bible. Even Spinoza declared that some would find strange his attempt to treat of human desires "in exactly the same manner as though I were concerned with lines, planes, and solids."

Blaise Pascal (1623–1662) was a French scientist who sought to keep science and religion united. He had a brief, but checkered career. For a short time, he was a reader of Montaigne and a companion of freethinkers. An accomplished scientist and brilliant mathematician, he excelled at both the practical, by inventing a calculating machine, and the abstract, by devising a theory of chance or probability and doing work on conic sections. After a profound mystical vision on the night of November 23, 1654, which assured him that God cared for the human soul, he devoted the rest of his life to religious matters. He planned to write an "Apology for the Christian Religion" but died before he could do so. He did leave a set of notes for the larger work, however, which in published form became known as *Pensées* or *The Thoughts*.

In *Pensées,* Pascal tried to convert rationalists to Christianity by appealing both to their reason and to their emotions. Humans were, he argued, frail creatures, often deceived by their senses, misled by reason, and battered by their emotions. And yet they were beings whose very nature involved thinking: "Man is but a reed, the weakest in nature; but he is a thinking reed. . . . Our whole dignity consists, therefore, in thought. By thought we must raise ourselves. . . . Let us endeavor, then, to think well; this is the beginning of morality."[26]

Pascal was determined to show that the Christian religion was not contrary to reason: "If we violate the principles of reason, our religion will be absurd, and it will be laughed at." Christianity, he felt, was the only religion that recognized people's true state of being as both vulnerable and great. To a Christian, a human being was both fallen and at the same time God's special creation. But it was not necessary to emphasize one at the expense of the other—to view humans as only rational or only hopeless. Thus,

PASCAL. **Blaise Pascal was a brilliant scientist and mathematician who hoped to keep science and Christianity united. In the *Pensées,* he made a passionate argument on behalf of the Christian religion. He is pictured here in a posthumous portrait by Quesnel.**

"knowledge of God without knowledge of man's wretchedness leads to pride. Knowledge of man's wretchedness without knowledge of God leads to despair. Knowledge of Jesus Christ is the middle course, because by it we discover both God and our wretched state." Pascal even had an answer for skeptics in his famous wager. God is a reasonable bet; it is worthwhile to assume that God exists. If he does, then we win all; if he does not, we lose nothing.

Despite his background as a scientist and mathematician, Pascal refused to rely on the scientist's world of order and rationality to attract people to God: "If we submit everything to reason, there will be no mystery and no supernatural element in our religion." In the new cosmology of the seventeenth century, "finite man," Pascal believed, was lost in the new infinite world, a realization that frightened him: "The eternal silence of those infinite spaces strikes me with terror" (see the box on p. 481). The world of nature, then, could never reveal God: "Because they have failed to contemplate these infinites, men have rashly plunged into the examination of nature, as though they bore some proportion to her. . . . Their assumption is as infinite as their object." A Christian could only rely on a God who through Jesus cared for human beings. In the final analysis, after providing reasonable arguments for Christianity, Pascal came to rest on faith. Reason, he believed, could take people only so far: "The heart has its reasons of which the reason knows nothing." As a Christian, faith was the final step: "The heart feels God, not the reason. This is what constitutes faith: God experienced by the heart, not by the reason."[27]

Pascal: "What Is a Man in the Infinite?"

Perhaps no intellectual in the seventeenth century gave greater expression to the uncertainties generated by the cosmological revolution than Blaise Pascal. Himself a scientist, Pascal's mystical vision of God's presence caused him to pursue religious truths with a passion. His work, the Pensées, *consisted of notes for a larger, unfinished work justifying the Christian religion. In this selection, Pascal presents his musings on the human place in an infinite world.*

Blaise Pascal, *Pensées*

Let man then contemplate the whole of nature in her full and exalted majesty. Let him turn his eyes from the lowly objects which surround him. Let him gaze on that brilliant light set like an eternal lamp to illumine the Universe; let the earth seem to him a dot compared with the vast orbit described by the sun, and let him wonder at the fact that this vast orbit itself is no more than a very small dot compared with that described by the stars in their revolutions around the firmament. But if our vision stops here, let the imagination pass on; it will exhaust its powers of thinking long before nature ceases to supply it with material for thought. All this visible world is no more than an imperceptible speck in nature's ample bosom. No idea approaches it. We may extend our conceptions beyond all imaginable space; yet produce only atoms in comparison with the reality of things. It is an infinite sphere, the center of which is everywhere, the circumference nowhere. In short, it is the greatest perceptible mark of God's almighty power that our imagination should lose itself in that thought.

Returning to himself, let man consider what he is compared with all existence; let him think of himself as lost in his remote corner of nature; and from this little dungeon in which he finds himself lodged—I mean the Universe—let him learn to set a true value on the earth, its kingdoms, and cities, and upon himself. What is a man in the infinite? . . .

For, after all, what is a man in nature? A nothing in comparison with the infinite, an absolute in comparison with nothing, a central point between nothing and all. Infinitely far from understanding these extremes, the end of things and their beginning are hopelessly hidden from him in an impenetrable secret. He is equally incapable of seeing the nothingness from which he came, and the infinite in which he is engulfed. What else then will he perceive but some appearance of the middle of things, in an eternal despair of knowing either their principle or their purpose? All things emerge from nothing and are borne onward to infinity. Who can follow this marvelous process? The Author of these wonders understands them. None but He can.

In retrospect, it is obvious that Pascal failed to achieve his goal of uniting Christianity and science. Increasingly, the gap between science and traditional religion grew wider as Europe continued along its path of secularization. Of course, traditional religions were not eliminated, nor is there any evidence that churches had yet lost their numbers. That would happen later. Nevertheless, more and more of the intellectual, social, and political elites began to act on the basis of secular rather than religious assumptions.

The Spread of Scientific Knowledge

In the course of the seventeenth century, scientific learning and investigation began to increase dramatically. Major universities in Europe established new chairs of science, especially in medicine. Royal and princely patronage of individual scientists became an international phenomenon. The king of Denmark constructed an astronomical observatory for Tycho Brahe; Emperor Rudolf II hired Tycho Brahe and Johannes Kepler as imperial mathematicians; the grand duke of Tuscany appointed Galileo to a similar post. Of greater importance to the work of science, however, was the emergence of new learned societies and journals that enabled the new scientists to communicate their ideas to each other and to disseminate them to a wider, literate public.

The Scientific Societies

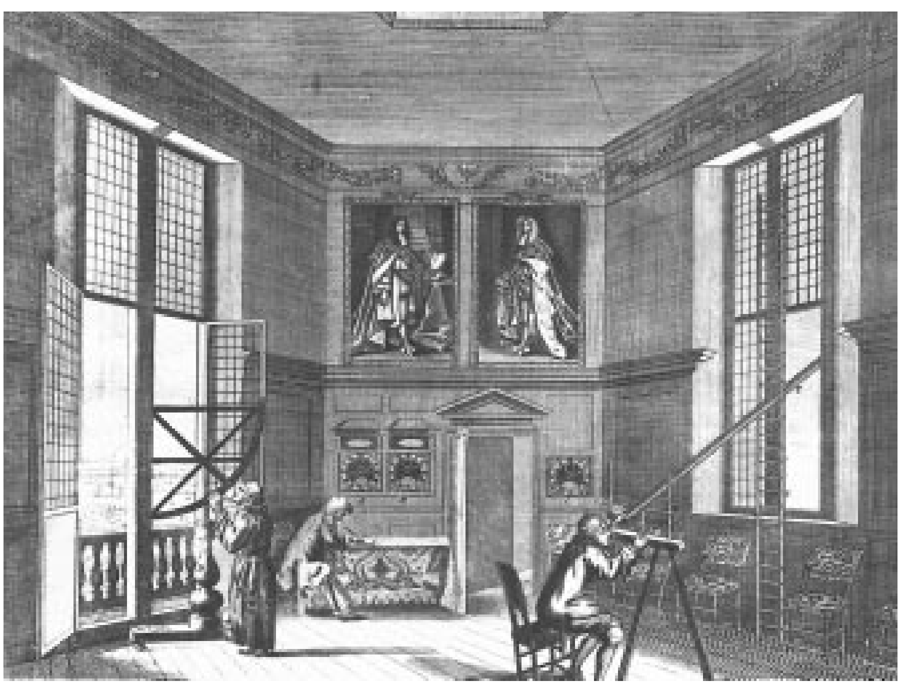
The first of these scientific societies appeared in Italy, but those of England and France were ultimately of more significance. The English Royal Society evolved out of informal gatherings of scientists at London and Oxford in the 1640s, although it did not receive a formal charter from King Charles II until 1662. The French Royal Academy of Sciences also arose out of informal scientific meetings in Paris during the 1650s. In 1666, urged on by his minister Colbert, Louis XIV formally recognized the group. The French Academy received abundant state support and remained under government control; its members were appointed and paid salaries by the state. In contrast, the Royal Society of England received little government encouragement, and its fellows simply co-opted new members.

Early on, both the English and French scientific societies formally emphasized the practical value of scientific research. The Royal Society established a committee to investigate technological improvements for industry while

LOUIS XIV AND COLBERT VISIT THE ACADEMY OF SCIENCES. In the seventeenth century, individual scientists received royal and princely patronage, and a number of learned societies were established. In France, Louis XIV, urged on by his minister Colbert, gave formal recognition to the French Academy in 1666. In this painting by Henri Testelin, Louis XIV is shown seated, surrounded by Colbert and members of the French Royal Academy of Sciences.

the French Academy collected tools and machines. This concern with the practical benefits of science proved short-lived, however, as both societies came to focus their primary interest on theoretical work in mechanics and astronomy. The construction of observatories at Paris in 1667 and at Greenwich, England, in 1675 greatly facilitated research in astronomy by both groups. The French Academy, however, since it was controlled by the state, was forced by the war minister of France, the marquis de Louvois, to continue its practical work to benefit both the "king and the state." The French example was especially important as a model for the scientific societies established in neighboring Germany. German princes and city governments encouraged the foundation of small-scale scientific societies of their own. Most of them, such as the Scientific Academy created in 1700 by the elector of Brandenburg, as well as the scientific academies established in most European countries in the eighteenth century, were sponsored by governments and were mainly devoted to the betterment of the state. Although both the English and French societies made useful contributions to scientific knowledge in the second half of the seventeenth century, their true significance arose from their example that science should proceed as a cooperative venture.

Scientific journals furthered this concept of cooperation. The French *Journal des Savants,* published weekly beginning in 1665, printed results of experiments as well as general scientific knowledge. Its format appealed to both scientists and the educated public interested in the new science. The *Philosophical Transactions* of the Royal Society, however, also initiated in 1665, published papers of its members and learned correspondence and was aimed at practicing scientists. It became a prototype for the scholarly journals of later learned and academic societies and a crucial instrument for circulating news of scientific and academic activities.



THE ROYAL OBSERVATORY AT GREENWICH. To facilitate their astronomical investigations, both the English and the French constructed observatories, such as the one pictured here, which was built at Greenwich, England, in 1675. Here the royal astronomer works at the table while his two assistants make observations.

Science and Society

The importance of science in the history of modern Western civilization is usually taken for granted. No doubt the Industrial Revolution of the nineteenth century provided tangible proof of the effectiveness of science and ensured its victory over Western minds. But how did science become such an integral part of Western culture in the seventeenth and eighteenth centuries? Recent research has stressed that one cannot simply assert that people perceived that science was a rationally superior system. Two important social factors, however, might help to explain the relatively rapid acceptance of the new science.

It has been argued that the literate mercantile and propertied elites of Europe were attracted to the new science because it offered new ways to exploit resources for profit. Some of the early scientists made it easier for these groups to accept the new ideas by showing how they could be applied directly to specific industrial and technological needs. Galileo, for example, consciously sought an alliance between science and the material interests of the educated elite when he assured his listeners that the science of mechanics would be quite useful "when it becomes necessary to build bridges or other structures over water, something occurring mainly in affairs of great importance." At the same time, Galileo stressed that science was fit for the "minds of the wise" and not for "the shallow minds of the common people." This made science part of the high culture of Europe's wealthy elites at a time when that culture was being increasingly separated from the popular culture of the lower classes (see Chapter 17).

It has also been argued that political interests used the new scientific conception of the natural world to bolster social stability. One scholar has recently argued that "no single event in the history of early modern Europe more profoundly shaped the integration of the new science into Western culture than did the English Revolution (1640–1660)."[28] Fed by their millenarian expectations that the end of the world would come and usher in a 1,000-year reign of the saints, Puritan reformers felt it was important to reform and renew their society. They seized on the new science as a socially useful instrument to accomplish this goal. The Puritan Revolution's role in the acceptance of science, however, stemmed even more from the reaction to the radicalism spawned by the revolutionary ferment. The upheavals of the Puritan Revolution gave rise to groups, such as the Levellers, Diggers, and Ranters, who advocated not only radical political ideas, but also a new radical science based on Paracelsus and the natural magic associated with the Hermetic tradition. The chaplain of the New Model Army said that the radicals wanted "the philosophy of Hermes, revived by the Paracelsian schools." The propertied and educated elites responded vigorously to these challenges to the established order by supporting the new mechanistic science and appealing to the material benefits of science. Hence, the founders of the Royal Society were men who wanted to pursue an experimental science that would remain detached from radical reforms of church and state. Although willing to make changes, they now viewed those changes in terms of an increase in food production and commerce. By the eighteenth century, the Newtonian world-machine had been readily accepted, and Newtonian science would soon be applied to trade and industry by a mercantile and landed elite that believed that they "could retain a social order that primarily rewarded and enriched themselves while still improving the human condition."

CHRONOLOGY

The Impact of the Scientific Revolution: Important Works

Bacon, *The Great Instauration*	1620
Descartes, *Discourse on Method*	1637
Pascal, *Pensées*	1669
Spinoza, *Ethics Demonstrated in the Geometrical Manner*	1677

CONCLUSION

The Scientific Revolution represents a major turning point in modern Western civilization. In the Scientific Revolution, the Western world overthrew the medieval, Ptolemaic-Aristotelian worldview and arrived at a new conception of the universe: the sun at the center, the planets as material bodies revolving around the sun in elliptical orbits, and an infinite rather than finite world. With the changes in the conception of "heaven" came changes in the conception of "earth." The work of Bacon and Descartes left Europeans with the separation of mind and matter and the belief that by using only reason they could, in fact, understand and dominate the world of nature. The development of a scientific method furthered the work of scientists while the creation of scientific societies and learned journals spread its results. Although traditional churches stubbornly resisted the new ideas and a few intellectuals pointed to some inherent flaws, nothing was able to halt the replacement of the traditional ways of thinking by new ways of thinking that created a more fundamental break with the past than that represented by the breakup of Christian unity in the Reformation.

The Scientific Revolution forced Europeans to change their conception of themselves. At first, some were appalled and even frightened by its implications. Formerly, humans on earth had been at the center of the universe. Now the earth was only a tiny planet revolving around a sun that was itself only a speck in a boundless universe. Most people remained optimistic despite the apparent blow to human dignity. After all, had Newton not demonstrated that the universe was a great machine governed by natural laws? Newton had found one—the universal law of gravitation. Could others not find other laws? Were there not natural laws governing every aspect of human endeavor that could be found by the new scientific method? Thus, the Scientific Revolution leads us logically to the age of the Enlightenment of the eighteenth century.

NOTES

1. Quoted in Alan G. R. Smith, *Science and Society in the Sixteenth and Seventeenth Centuries* (London, 1972), p. 59.
2. Edward MacCurdy, *The Notebooks of Leonardo da Vinci* (London, 1948), 1:634.
3. Ibid., p. 636.
4. Frances Yates, *Giordano Bruno and the Hermetic Tradition* (New York, 1964), p. 448.
5. Ibid., p. 450.
6. Quoted in Smith, *Science and Society in the Sixteenth and Seventeenth Centuries,* p. 97.
7. Logan P. Smith, *Life and Letters of Sir Henry Wotton* (Oxford, 1907), 1:486–487.
8. Quoted in John H. Randall, *The Making of the Modern Mind* (Boston, 1926), p. 234.
9. Quoted in Smith, *Science and Society in the Sixteenth and Seventeenth Centuries,* p. 124.
10. Quoted in Betty J. Dobbs, *The Foundations of Newton's Alchemy* (Cambridge, 1975), pp. 13–14.
11. Jolande Jacobi, ed., *Paracelsus: Selected Writings* (New York, 1965), pp. 5–6.
12. Ibid., p. 21.
13. Quoted in Londa Schiebinger, *The Mind Has No Sex? Women in the Origins of Modern Science* (Cambridge, Mass., 1989), pp. 52–53.
14. Ibid., p. 85.
15. Galen, *On the Usefulness of the Parts of the Body,* trans. Margaret May (Ithaca, N.Y., 1968), 2:628–629.
16. Quoted in Phyllis Stock, *Better Than Rubies: A History of Women's Education* (New York, 1978), p. 16.
17. René Descartes, *Philosophical Writings,* ed. and trans. Norman K. Smith (New York, 1958), p. 95.
18. Ibid., pp. 118–119.
19. Ibid., p. 120.
20. Francis Bacon, *The Great Instauration,* trans. Jerry Weinberger (Arlington Heights, Ill., 1989), pp. (in order of quotations) 2, 8, 2, 16, 21.
21. Descartes, *Discourse on Method,* in *Philosophical Writings,* p. 75.
22. Stillman Drake, ed. and trans., *Discoveries and Opinions of Galileo* (New York, 1957), p. 182.
23. Benedict de Spinoza, *Ethics,* trans. R. H. M. Elwes (New York, 1955), pp. 75–76.
24. Ibid., p. 76.
25. Benedict de Spinoza, *Letters,* quoted in Randall, *The Making of the Modern Mind,* p. 247.
26. Blaise Pascal, *The Pensées,* trans. J. M. Cohen (Harmondsworth, 1961), p. 100.
27. Ibid., pp. (in order of quotations) 31, 45, 31, 52–53, 164, 165.
28. Margaret C. Jacob, *The Cultural Meaning of the Scientific Revolution* (New York, 1988), p. 73.

SUGGESTIONS FOR FURTHER READING

Four general surveys of the entire Scientific Revolution are A. G. R. Smith, *Science and Society in the Sixteenth and Seventeenth Centuries* (London, 1972); J. R. Jacob, *The Scientific Revolution: Aspirations and Achievements, 1500–1700* (Atlantic Highlands, N.J., 1998); S. Shapin, *The Scientific Revolution* (Chicago, 1996); and J. Henry, *The Scientific Revolution and the Origins of Modern Science* (New York, 1997). Also of much value is A. G. Debus, *Man and Nature in the Renaissance* (Cambridge, 1978), which covers the period from the mid-fifteenth through the mid-seventeenth century. On the relationship of magic to the beginnings of the Scientific Revolution, see the pioneering works by F. Yates, *Giordano Bruno and the Hermetic Tradition* (New York, 1964), and *The Rosicrucian Enlightenment* (London, 1975). Some criticism of this approach is provided in R. S. Westman and J. E. McGuire, eds., *Hermeticism and the Scientific Revolution* (Los Angeles, 1977).

A good introduction to the transformation from the late medieval to the early modern worldview is A. Koyré, *From the Closed World to the Infinite Universe* (New York, 1958). Also still of value is A. Koestler, *The Sleepwalkers: A History of Man's Changing Vision of the Universe* (New York, 1959). On the important figures of the revolution in astronomy, see E. Rosen, *Copernicus and the Scientific Revolution* (New York, 1984); M. Sharratt, *Galileo: Decisive Innovator* (Oxford, 1994); S. Drake, *Galileo, Pioneer Scientist* (Toronto, 1990); M. Casper, *Johannes Kepler,* trans. C. D. Hellman (London, 1959), the standard biography; and R. S. Westfall, *The Life of Isaac Newton* (New York, 1993). On Newton's relationship to alchemy, see the invaluable study by B. J. Dobbs, *The Foundations of Newton's Alchemy* (Cambridge, 1975); and M. White, *Isaac Newton: The Last Sorcerer* (Reading, Mass., 1997).

The worldview of Paracelsus and his followers can be examined in A. G. Debus, *The Chemical Philosophy: Paracelsian Science and Medicine in the Sixteenth and Seventeenth Centuries,* 2 vols. (New York, 1977). The standard biography of Vesalius is C. D. O'Malley, *Andreas Vesalius of Brussels, 1514–1564* (Berkeley, 1964). The work of Harvey is discussed in G. Whitteridge, *William Harvey and the Circulation of the Blood* (London, 1971). A good general account of the development of medicine can be found in W. P. D. Wightman, *The Emergence of Scientific Medicine* (Edinburgh, 1971).

The importance of Francis Bacon in the early development of science is underscored in P. Zagorin, *Francis Bacon* (Princeton, N.J., 1998). A good introduction to the work of Descartes can be found in G. Radis-Lewis, *Descartes: A Biography* (Ithaca, N.Y., 1998). The standard biography of Spinoza in English is S. Hampshire, *Spinoza* (New York, 1961).

For histories of the scientific academies, see R. Hahn, *The Anatomy of a Scientific Institution: The Paris Academy of Sciences, 1666–1803* (Berkeley, 1971); and M. Purver, *The Royal Society, Concept and Creation* (London, 1967).

On the subject of women and early modern science, see the comprehensive and highly informative work by L. Schiebinger, *The Mind Has No Sex? Women in the Origins of Modern Science* (Cambridge, Mass., 1989). See also C. Merchant, *The Death of Nature: Women, Ecology, and the Scientific Revolution* (San Francisco, 1980). There is a chapter on Maria Sibylla Merian in N. Davis, *Women on the Margins* (Cambridge, Mass., 1995). The social and political context for the triumph of science in the seventeenth and eighteenth centuries is examined in M. Jacobs, *The Cultural Meaning of the Scientific Revolution* (New York, 1988), and *The Newtonians and the English Revolution, 1689–1720* (Ithaca, N.Y., 1976).

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