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THE BEDFORD SERIES IN HISTORY AND CULTURE

The Scientific Revolution

A Brief History with Documents

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PART ONE

Introduction: The Evolution and Impact of the Scientific Revolution

In 1600, most Europeans stood on the earth, looked into the heavens, and confidently assumed that they were standing at the center of the universe. In that year, only a handful of people accepted Copernicus's argument, first made in 1543, that the sun, and not the earth, occupied the central place in our cosmos. As a learned Spanish Jesuit put the matter in 1590, "It is truly a wonderful thing to see how elegantly and gracefully Holy Writ" explains "that the earth and sea form a globe in the midst of the universe." By 1700, many educated people, especially in northern and western Europe, knew that Copernicus had been right and also knew that Isaac Newton's law of universal gravitation governed the motion of all the planets in relation to a stationary sun. By 1750, no European or American colonial could be considered educated if he or she still believed that the earth stood still and in the center of the universe, as the sun revolved around it. Even pocket almanacs or calendars aimed at the most general reader had begun to stop referring to a moving sun.[1]

The profound shift in the Western understanding of physical nature between the sixteenth and eighteenth centuries quickly acquired a shorthand description: the Scientific Revolution. Some have said that the phrase is misleading because it applies a political word—revolution—with all its implied suddenness, to a transformation that took well over a century and a half to unfold. But sometimes evolutionary change can have a revolutionary impact. Scientific method is one of the distinctive features of modernity everywhere in the world, and, not surprisingly, those who hate the modern world are often hostile to science or favor occult or mystical forces that will provide an alternative set of explanations. Much more about nature than simply the physical mass placed in the center of the cosmos—the sun being substituted for the earth—altered as a result of the intellectual and cultural transformations brought about by the Scientific Revolution.

WHY DID THE SCIENTIFIC REVOLUTION HAPPEN?

The most challenging question is trying to determine why this transformation from ancient understandings of nature occurred in western Europe after 1500. This question is related to a larger one: Why did the West come to a position of global dominance by 1850? Much self-congratulation has accompanied many of the answers offered by Western historians over the years. But from any perspective, before 1700, China and much of Southeast Asia were technologically ahead of the West and just as intellectually vibrant. Chinese farmers could produce more food per acre and thus support the populations of far larger cities than those in the West. During the so-called Middle Ages of Europe, Arabic science and medicine were far in advance of Western science, and Arab scientists had extensive knowledge of ancient writers nearly forgotten in Europe. As one commentator notes, "Until 1750, changes in population, agriculture, technology, and living standards were not fundamentally different in eastern Asia from those in Western Europe." But by that date in the West, most universities in the northern areas of Europe and North America had stopped teaching Aristotle exclusively and had begun to teach the science and natural philosophy of Newton.[2]

Yet the land mass far to the west of China (what is called western Europe) had certain distinct characteristics that no one would have predicted to be advantageous. It was broken into rival and sovereign states, each possessing a different language. Although the Chinese emperor could control the ideas of his mandarin elite, no one in England could control what was being said—or published—in France. Even the Catholic Holy Roman Emperor could not stop people from becoming Protestants in his kingdom. The German-speaking areas of Europe in the sixteenth century were highly fragmented, with local princes and regions often going their separate ways and opting for the religion that they found most attractive. Relative to the power and hegemony of non-Western states, Western kings were weak. No common written language existed except Latin, and probably no more than 5 percent of the population could read it. Only the Christian church provided a universal point of reference to which rich and poor alike could respond.

After the Protestant Reformation began in 1517, the universalism of the Catholic Church was shattered, and Protestantism made deep inroads in many parts of Europe. More than a century of religious wars followed. If there was any single "cause" that made a few Europeans break with intellectual tradition and study nature differently, it was religious conflict. Catholics doubted the truth of Protestantism and vice versa, and doubt can be infectious. If something as venerable as the church could be questioned, even disdained, might not other truths bear scrutiny? Centers of non-clerical learning had emerged in the highly urbanized parts of Europe, on the Italian peninsula and in the Low Countries (including what is today parts of western Germany, the Netherlands, Belgium, and Luxembourg), as well as in London and Paris. Royal courts provided patronage and facilities where naturalists could work, presumably to enhance the glory of their princes. New forms of knowledge could flourish in places other than the universities, uniformly controlled as they were by the clergy, either Protestant or Catholic. Reformers intent on generating new knowledge about nature could gravitate to a court or a city. Access to the printing press was also vitally important. The competition to have naturalists, alchemists, and even astrologers at one's court made it impossible to keep their knowledge or experiments secret, leading to a science that was accessible to all who could read.

Historians still debate the causes of the Scientific Revolution. Some have argued that evidence from nature accumulated to the point that a major intellectual shift had to occur to accommodate it. Thus, these historians suggest that religious and social factors had little or nothing to do with the transformation away from Aristotle toward what came to be called the mechanical philosophy. Others have written books about the Scientific Revolution focused on a few great minds, claiming that the "revolution" never actually occurred. Still others have focused on the enduring role of the seemingly magical alchemy and questioned whether the so-called modern thinkers who ushered in the new science were really all that forward thinking.

The documents in this book provide evidence that a slow but real change occurred in the western European understanding of nature between 1550 and 1750 and that this shift had major implications for the development of the sciences, including medicine, as well as for advances in applied technology in everything from warfare to industry. The transformation toward a mechanical understanding of nature—the assumption that motion only occurs when bodies come into contact—was aided not only by new and better methods of observation but also by the expanded worldview of many Europeans as a result of overseas trade and exploration in the early modern era. Although theology dominated intellectual life in the sixteenth century, the seventeenth witnessed the emergence of more secular concerns, in part as a reaction to the turmoil unleashed by religious strife, by warfare between Catholics and Protestants. The continuous wars fought in the early modern period throughout Europe and against the Turks made the search for improved military technology a high priority. Competition, patronage, the printing press, the vitality of urban markets, and overseas trade and exploration all contributed to the rise of a new science. By 1800, universities were being founded—in Berlin, for example—that gave pride of place to "the scientific."

ARISTOTLE, PTOLEMY, AND THEIR EARLY MODERN DEFENDERS

When trying to understand the physical world, any educated person in early sixteenth-century Europe turned to the ancient philosopher Aristotle (384–322 BCE), as interpreted by generations of Christian scholars who controlled the great universities of Europe—Bologna in Italy, the Sorbonne in Paris, and Oxford and Cambridge in England. They proclaimed that only the principles of Aristotle, found in his *Physics* and interpreted by textbooks written by his followers, could explain why and how things moved, changed, or disintegrated. And Aristotle had said that the cause of change lies "in the nature of a thing."

Aristotle, as digested later by his many Christian followers and Arabic interpreters, stood as the most powerful influence in science until the seventeenth century. Certain aspects of Aristotelianism (often called *Scholasticism* because of its role in the curriculum of the schools) need emphasis. Aristotle saw the cosmos as a closed set of concentric spheres. At its center lay the earth. He believed the objects in the heavens were fixed and eternal, in effect perfect. If they moved, it was in perfectly circular orbits. The earth and things on or near its surface could degenerate or die, and the natural motions of earthly bodies that moved were rectilinear and perpendicular to the surface of the earth.

All natural substances were composed of matter and form. The stuff of which things were made—matter—had only the potential to be something. Only form could make matter into substance, imparting shape and the power to move. Form also determined the process or goal of a substance. Thus, rocks were endowed with heaviness by their form and naturally moved downward toward the earth, fire naturally rose, and plants and animals sought to reproduce and protect themselves. Humans were composed of form and matter, or soul and body, and they possessed an inherent goal of rationality. Immaterial forms shaped every physical thing, inanimate or living.

In the second century CE, the Alexandrian astronomer and mathematician Ptolemy (d. ca. 178 CE) fully articulated Aristotle's geocentric theory in the *Almagest*. Ptolemy wrote with what seemed to be common sense when he said that if the earth moved, people would be left riding in the air. Ptolemy appeared to explain what people on earth saw. Aristotle's ideas endured in part because they also proved flexible.

Christian philosophers easily adapted Aristotle to their ends; form became the immortal soul and its purpose lay in using reason to arrive at salvation. At the time of the Scientific Revolution, the most intellectually rigorous defense available of the Aristotelian position came from theologian and philosopher Francisco de Suarez (1548–1617). All the natural philosophers (who would later be called *scientists*) of the seventeenth century knew his writings well. It is impossible to comprehend the massive shift in ideas that occurred during the Scientific Revolution without understanding how Christian philosophers like the Jesuit Suarez described nature.[3]

Suarez articulated the central tenet of the Scholastic philosophy, the doctrine of form, which gave life, purpose, and meaning to matter. Forms could shape physical things, and they also had an existence beyond the physical—in the spiritual, or metaphysical—realm. Suarez wrote:

> It is indeed customary to divide form into physical and metaphysical; the prior . . . exerts true and real formal causality, and it is, therefore, that which we must treat most extensively. It is said to be a "physical form," either because it chiefly constitutes the nature of a thing, or because it is investigated principally through the analysis of physical change and is considered primarily in physics. Nevertheless, it is not outside the consideration of metaphysics. This is so, first, because the notion of "form" is common and abstract; then,

> because form constitutes the essence of a thing; and, finally, because it is one of the principal causes. . . . It should, therefore, be said that, besides matter, all natural or corporeal things consist of substantial form as their intrinsic principle and formal cause. This is the view of Aristotle in innumerable places.[4]

Because Scholastics like Suarez linked the central concept of Aristotelian form to the religious idea of the human soul, any attack on the notion of form as the key to understanding nature had immediate and dire religious implications. As a Catholic priest, Suarez wanted to see the church's doctrines fortified philosophically at a time when the Protestant Reformation was challenging the pope and bitterness infused the relationship between Catholics and Protestants. It is not a coincidence that the most systematic attacks on Aristotle originated in Protestant circles where defeating his understanding of nature appeared to repudiate Catholic learning. No Catholic doctrine and practice depended more on Aristotle's forms than the sacrament of the Eucharist. During the Mass, the priest had the power to transform bread and wine into the body and blood of Christ because the form of the matter could be changed without affecting its shape or appearance.

EXPLORATION AND TECHNOLOGICAL INNOVATION

The contestation and eventual displacement of Scholasticism did not occur in an intellectual vacuum, in minds divorced from everyday realities. It is not accidental that the attack on Aristotle coincided with the explosive growth of overseas trade and exploration. Suddenly, the Spanish, Portuguese, Dutch, English, and French were encountering people, plants, and animals never before imagined. With this opening of the European mind came much hardship and abuse for the peoples conquered or enslaved, or both. It also challenged the force of tradition and authority at home. Why had the ancient philosophers not foreseen the richness, complexity, and diversity that existed throughout the globe? Why is there no mention of the Americas in the Bible? By the mid-seventeenth century, Europeans' knowledge of distant people and places had grown exponentially. By 1700, more than 160 accounts had been published to describe the indigenous peoples of the Americas alone. Naturalists even vied for the chance to travel in the merchant ships bound for the New World, and the artist and naturalist Maria Sibylla Merian (1647–1717) went so far as to finance her own trip and that of her daughter to the Dutch colony of Suriname so that she could observe its plants, animals, bugs, and insects firsthand (see Document 14). So much movement of goods and people even suggested that a new mathematics was needed, one that could better express the movement of bodies.

In addition, travelers' encounters with Hindus, Muslims, and Jews—as well as the indigenous people of the New World—made it harder to assume that everything Western must by definition be right or universal. Francis Bacon (1561–1626), one of the intellectual lights of the Scientific Revolution, articulated the link between the new science and overseas exploration; it is God's will, he said, that "the circumnavigation of the world and the increase of the sciences should happen in the same age" (see Document 2).[5]

The global expansion of Europe occurred at a time of deep intellectual and religious ferment. The printing press, a German invention of the mid-fifteenth century, allowed for unprecedented access to books in every language and in every country. Protestants and Catholics debated their respective religious differences through print. In all countries, some form of censorship, often imposed by the clergy, sought to control what could be printed. Natural philosophers seized on the press for communicating their disagreement with Aristotle or their new theories and mathematical evidence about the way nature operated. Invented around the same time, copperplate engraving proved invaluable in scientific books intended to illustrate in detail what the naturalist had seen or discovered.

Many practitioners of the new science broke with tradition even in the language they used to communicate their findings. Instead of using Latin, the language of philosophy, they turned to their native languages and sought to reach an educated audience that might only read in Italian or French or English. Increasingly, the new natural philosophers published books containing pictures that reinforced abstract ideas or depicted new devices and machines, as well as showing the interior of the human body or the structure of insects.

Crafts such as lens grinding, engraving, and metal working were the domain of artisans, not intellectuals. Often overlooked in the study of the Scientific Revolution has been the artisanal contribution to its momentum, as hundreds of working men and women put into practice what would come to be seen as a new empirical science. In London alone by 1600, there were at least two thousand practitioners of science, women herbalists, male and female alchemists (alchemy was the pharmacology of the day), botanists, distillers, printers, machinists, and clock makers. All contributed innovative practices that added precision, rigor, and newly accumulated information, and they laid a foundation for what would eventually be called the Scientific Revolution.[6]

In addition, technological innovations helped spur the massive innovations in the Western understanding of nature. The new telescopes and microscopes of the age made possible investigations never before imagined. The improvement in lens grinding enabled these endeavors and also produced better and cheaper eyeglasses that expanded people's working lives and reading capabilities. Sometimes new technology permitted new science; other times, the relationship was reversed. For example, Galileo Galilei's (1564–1642) ability to "see" the earth's moon and the moons of Jupiter (see Document 4) was critically important to his success, but he had to know how to interpret what the improved telescope allowed him to see. He put his eye to the glass with a set of philosophical assumptions, and one was the uniformity of matter. Once he saw the shadows on the moon, he could postulate that the moon was a physical body.

Sometimes the science led to technological innovations. By 1700, the science of mechanics had been systematized with books and lectures explaining how better to distribute weight; how to use levers, pulleys, and balances to greater effect in everything from making better carriages to lifting water out of coal mines. Mechanical knowledge

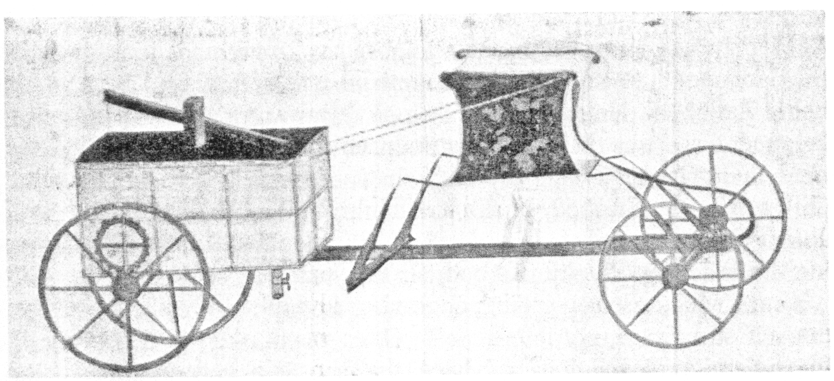

Figure 1. *A Steam-Powered Carriage, 1789.*
The engineer who made this carriage was thinking ahead of the times but only by a few years. The obvious next step with the steam engine lay in its application to transportation.
Courtesy of the Society of Antiquaries of Newcastle upon Tyne.

spread, and its penetration became particularly evident in eighteenth-century Britain. It is easily understood why the first steam engines came out of circles familiar with Robert Boyle's concept of the "weight of the air," what we call *air pressure*. The engine's rapid spread was the work of engineers familiar with Newtonian mechanics. By the late eighteenth century, its power had been applied to mining and manufacturing, and inventors were trying to figure out how it might be applied to transportation. It became what economists call a general-purpose technology (like computers today) and, by 1800, it would be adapted to a wide variety of tasks requiring power. By the mid-nineteenth century, the British possessed engines that delivered ten times the power of any that could be found in France. Innovation translated into national power and empire.

THE EMERGENCE OF THE SCIENTIFIC REVOLUTION

By the time of the Industrial Revolution (1780–1850), the vision of the Aristotelians had long since been dismantled. But dismantling that vision would take more than a century and require a series of philosophical challenges. Aristotle's natural philosophy gave an inherent purpose and motion to earthly objects and a distinctive and ethereal nature to heavenly ones. Its defeat required the recovery and adaptation of other ancient philosophies. The Italian Renaissance of the fifteenth and early sixteenth centuries had brought back into circulation long-forgotten philosophies by ancient philosophers such as Plato (ca. 428–348 BCE) and Epicurus (341–270 BCE). Plato emphasized the invisible forces at work in nature and argued that appearances could be deceiving. Mathematics held the key to nature and revealed its inherent harmony. The Epicureans are today largely remembered for wanting to have a good time, but that is a distortion of a basic philosophy that emphasized personal virtue. Europeans of the early modern period knew the thought of Epicurus largely through the poem by his follower Lucretius (ca. 99–55 BCE), *De rerum natura*. Its importance lay in the atomism it preached—that nature was composed of miniscule, hard corpuscles that randomly combine to create the bodies that can be seen by our eyes. It also proposed that there were multiple worlds, that our universe was not alone in the cosmos. Epicureans denied that all the bodies in nature possessed a goal, thus breaking with Aristotle's ideas about form and purpose.

Along with ancient atomism and the Platonic emphasis on mathematical elegance came the revival of the ancient philosophies of skepticism and Stoicism. As the religious wars of the sixteenth century intensified, both on the battlefields and in print, each of these philosophies seemed viable alternatives to competing religious dogmas and doctrines preached from whatever pulpit. The skeptics rejected the dogmatism found in both the Protestant and Catholic churches and argued that ultimate truth was not available to human beings. The Stoics urged that reason control the passions, especially in religious matters, and that detachment is the only ethically viable posture. Both skepticism and Stoicism played a role in offering alternatives to Aristotle and in lending support to aspects of the new science—its willingness to doubt received wisdom and its emphasis on slow, painstaking labor.

Seldom has a doctrine aroused greater animosity than the doctrine of forms, and, gradually and firmly, the new science discarded it. In its place came new practices and philosophical assumptions, what is generally called the *mechanical philosophy*. This philosophy assumed that all motion occurs as the result of contact between bodies. There are no inherent tendencies to either rest or move. Mathematics can best describe these motions, and it began to replace metaphysics as the tool for unlocking nature's secrets. As the metaphysical assumption of form was discarded, new atomic explanations for matter and motion replaced it. Matter was composed of small, hard, impenetrable bodies. Some called them *corpuscles* and said that they could be divided infinitely. Others called them *atoms*, the smallest, hard and impenetrable material of which things in nature are composed. The motion of bodies became possible not because form "told" them how to move; rather, they moved if they were hit by another body. If they were not hit, they remained inert. The Western thinkers who rejected Scholasticism and established the theories, proofs, and practices that became known as the Scientific Revolution redefined physical matter, motion, space and time, the nature of light, the substance and orbits of the heavenly bodies, the value of mathematics and its ability to describe moving bodies, and, not least, the motions of the human body from the circulation of blood to the structure of the lymphatic system.

THE NEW SCIENCE

Many historians of the Scientific Revolution date its beginning to Nicolaus Copernicus (1473–1543). Raised by a pious uncle who eventually became a bishop, Copernicus also held a church office; his intellectual

interests, however, were in studying physical nature, the heavens, and the human body. As a young student at Cracow University in what is today Poland, Copernicus studied Aristotelian philosophy. After studying at Bologna where he probably encountered the writings of Plato, Copernicus began lecturing in mathematics and studying astronomy. In addition, he was a doctor of canon law and a physician. In 1540, one of his pupils, Rheticus, began to circulate the idea that the earth moved around the sun, not vice versa. Copernicus agreed to publish the theory he had been teaching in *De Revolutionibus orbium coelestium* (see Document 1). Legend has it that Copernicus received the final proof sheets of the book when on his deathbed in May 1543, months before the book was published. In articulating a heliocentric theory of the universe, Copernicus broke with Aristotle and his ancient follower Ptolemy.[7] By no means, however, was Copernicus immediately accepted. Decades later, Suarez wrote as if Copernicus was irrelevant. As all Copernicus's contemporaries knew, it is not self-evident that the earth moves. But Copernicus believed that by simplifying the mathematics needed to explain the motions of the planets, he had edged closer to philosophical truth.

Copernicus was also a medical doctor, and he would have known about new developments in medicine. By the mid-sixteenth century, medical reform was very much a burning issue. A contemporary of Copernicus, Andreas Vesalius (1514–1564), produced a massive work in seven volumes, *On the Structure of the Human Body* (1543), that gave the world the most detailed study ever done on every aspect of the human body. Its use of engraving to illustrate every organ, muscle, and fiber was unprecedented and provided a kind of "map" that other anatomists and physicians used for decades.

Observation was also a critical part of the new aesthetic at the root of innovative science. Tycho Brahe (1546–1601) took planetary observation to new standards of accuracy and even discovered new stars. He did all of this without accepting Copernican heliocentrism, thus illustrating that observation could flourish independently from the bold theoretical claims that would come to define the new science. Perhaps his greatest contribution to the new science came from his decision to hire the young German Johannes Kepler (1571–1630). Possibly out of jealousy at Kepler's brilliance, Brahe set him up with the nearly impossible task of plotting the orbit of Mars by using Brahe's observations. Gradually, almost painfully, Kepler came to see that Aristotle must have been wrong when he decreed that all motion in the heavens had to be perfectly circular. Only a flattened circle, an ellipse, Kepler realized, could account for all the places that Mars ventures as it circumnavigates the sun. With that insight, he went on to formulate three laws of planetary motion that proved to be critical for the work done by seventeenth-century natural philosophers.

Note that so far we have been describing the contributions made by a Pole (Copernicus), a Belgian (Vesalius), a Dane (Brahe), an Italian (Galileo), and a German (Kepler). An international conversation that transcended national and linguistic borders as well as religious convictions characterized the early decades of the new scientific inquiry. That would change gradually over the course of the seventeenth century as science became increasingly a northern European phenomenon with a strongly Protestant demography. Intellectual preeminence in science became associated with the English, Dutch, and French.

Inspired by the Protestant Reformation, Francis Bacon began the intellectual assault on scholastic practices. Bacon often gets credit for singlehandedly advancing the cause of English science when in fact he was riding on the crest of a wave of scientific practitioners at work in London during the reign of Elizabeth I (r. 1558–1603) and beyond. Bacon's education at Cambridge University left him with a lifelong dislike of Aristotle and his interpreters, while his career as a lawyer encouraged his bent toward research and empirical evidence. He believed that what the age called "politiques" (politics) should be the calling of a few gifted and experienced men, eager to serve their princes. Bacon spent his life essentially in two pursuits: advancement at court, first under Elizabeth I and then more spectacularly under King James I (r. 1603–1625). Just as earnestly, Bacon worked to lay the foundations for new attitudes toward learning, in particular the study of the natural world. The second of these activities made him famous among the educated and eventually inspired the new adjective "Baconian." It described the detailed examination of nature, a collecting and sifting, an interrogation of it with an eye toward useful application. Bacon also advocated that the king and the state take up the cause of science (see Document 2).

Bacon urged his readers to get out into nature—to explore, to test, to experience—in the search for human improvement, possibly even perfectibility (see Document 3). Bacon wanted learning to become a way to God similar to what the Bible offered. God's work would complement his word. As a servant of the prince and his state, Bacon also realized that science could enhance the power of the state. He was the first to see what many European and eventually American governments came to believe—that science in the service of the state increases its power. Baconianism came to be associated with the dedication to science and utility found in philosophical circles throughout northern Europe. When the French revolutionaries of the 1790s opened the first ever exposition of industrial technology and fine craftsmanship, they invoked Bacon as their inspiration.[8]

THE MECHANICAL PHILOSOPHY

Beginning in the late 1580s, Galileo Galilei began the process by which the central tenets of the mechanical philosophy were put into place. Born in Pisa, Galileo started life within a learned, artisanal household. His father possessed musical and mathematical skills, and Galileo received an education first from a private tutor and then at the university in Pisa. His background gave him enormous self-confidence. Increasingly, Galileo's interests drew him to mathematics and physics. Around 1583, he discovered that when taking small swings, a pendulum always swings to and fro in the same period of time regardless of the length of the swing.

Circumstances drew Galileo to Florence where his research into natural phenomena expanded in new and exciting directions. He earned the respect and patronage of the Florentine court and was connected with high society in both church and state.

Early in his career, Galileo came to oppose Aristotle's influence on the physical sciences. Galileo was able to demonstrate that bodies of unequal weight fall at the same speed, a principle that contradicted the Scholastic notion that the weight of a body determined its trajectory. Galileo's discoveries laid the foundation for a mechanical understanding of nature and the idea that bodies remain at rest until hit by another body and not because of a condition "natural" to them. Central to the mechanical understanding of nature lay the notion that all of nature is composed of matter in motion. In *The Starry Messenger*, published in 1610 (Document 4), Galileo argued that the matter in the heavens is the same as that on earth. His work depended on Copernican theory, skepticism toward the Scholastics, and a good measure of observation. Galileo was convinced that Copernicus was right. Because the moon revolved around the earth, the moon's being a body added weight to the Copernican hypothesis; why could not the earth, another body, revolve around the sun? Having seen the contours of the earth's moon, the four moons of Jupiter, and new planets through his superior telescope, Galileo proclaimed that the earth and the heavens are made of the same material substance.

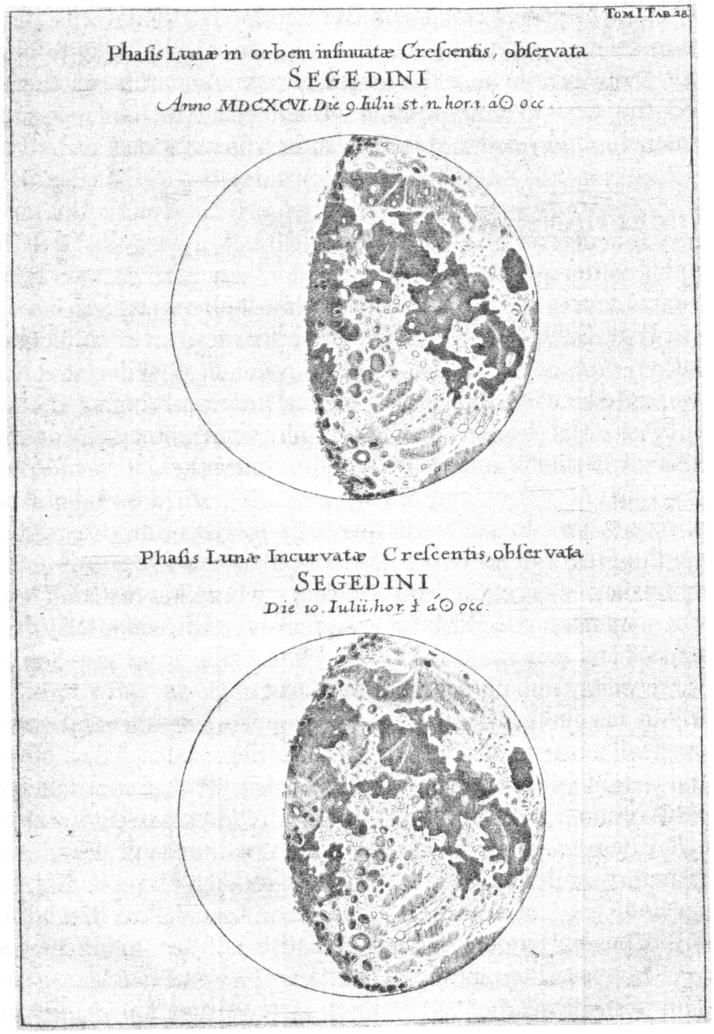

Figure 2. *Galileo Galilei, Two Illustrations of the Moon, 1610.*
Galileo's knowledge of artistic technique—that is, the use of lighter and darker shades to denote distance and contours—may have been critical to the way he saw the moon. Once his eye spotted the shadows on it, he concluded that what he observed could only be physical shapes. The moon became a physical body, not a ball of ethereal light and, like the earth it possessed mountains and valleys (see Document 4).

Department of Special Collections, Charles E. Young Research Library, UCLA.

As a devout Catholic, Galileo knew that his heliocentric assumption would not sit well with the Roman Catholic Church. Indeed in 1616, the church had condemned the Copernican argument because it said that the argument contradicted passages in the Bible. In the early 1630s, Galileo took up his pen and defended Copernicus even though the church had expressly forbidden such defense. Because the Bible suggested that the earth stood still and because the church reserved the right to interpret matters of truth—even in natural philosophy—the church put Galileo on trial for heresy. The church may also have believed that Galileo's embrace of a form of atomism introduced a theory of matter that would ultimately undermine the doctrine of transubstantiation, the belief that the priest has the power to change the form of bread and wine, turning it into the body and blood of Christ.

In 1633, the Catholic Inquisition in Rome declared "that you, the said Galileo, by reason of the matters adduced in trial . . . have rendered yourself . . . vehemently suspected of heresy, namely, of having believed . . . that the sun is the center of the world and does not move from east to west and that the earth moves and is not center of the world."[9] Galileo was fortunate in only being condemned to house arrest and not prison—or worse. At an official ceremony in 1992, Pope John Paul II admitted that the church had made a grave error. But in Galileo's lifetime and long after, his overconfident challenge to papal authority was ignored, and for supporters of the new science he became one of its "martyrs."[10]

At the same time that Galileo and others were making enormous advances in physics, mathematics, and astronomy, other scientists turned to experiments on animals to try to better understand the functioning of corporeal bodies. William Harvey (1578–1657), trained in medicine and anatomy at Padua, was educated in the doctrines of the Greek physician Galen (ca. 130–201) who largely followed Aristotle. Thus Harvey believed himself to be working in the tradition of Aristotelian medicine when he did his anatomical work, using, as was the custom, live dogs so that the flow of blood could be observed as it was happening. He was not so much experimental as observational when he argued that logic dictates that blood circulates (see Document 5). Harvey taught anatomy and surgery at London's Royal College of Physicians. Being both innovative and Aristotelian was still possible in Harvey's lifetime, although his would be the last generation in England in which that combination remained credible.

The Catholic Church's opposition to Copernicanism had very real effects on the life of perhaps the most important mechanical thinker of the Scientific Revolution, René Descartes (1596–1650). No one natural philosopher in the period from 1600 to 1700 did more to put the mechanical philosophy in place than Descartes. Educated by Jesuits at one of the best schools in France, Descartes was among the pupils who read about Galileo's great discoveries in *The Starry Messenger*. Descartes grew up in an age of religious wars between Catholics and Protestants. In reaction, some philosophers turned to skepticism as the only civilized response to such bloodshed; why not doubt everything when true believing leads to death, destruction, and the collapse of social order? As an antidote, Descartes sought to create a method for arriving at clear and distinct ideas guided only by reason and to illustrate it by three experiments with natural objects. Following Galileo's condemnation in 1633, Descartes removed himself to the Protestant Dutch Republic. He was deeply influenced by Galileo, knew the arguments of Bacon, and believed that a mechanical understanding of nature—that it is made of minuscule corpuscles and that contact between bodies accounts for motion—was the only foundation on which to build a new science. These principles applied not only to earthly motion but also to the motion of the planets. Descartes embraced the mechanical philosophy as part of a life-altering, moral enterprise that required an entirely new intellectual posture in the world. Descartes explained that nature had mathematical laws and that the matter of the universe was not only uniform but also put—and kept—in motion because of these laws. And Descartes made the study of these mathematical laws into an ethical enterprise, a search for truth that was public, open, modest (at least rhetorically), and (theoretically) available to anyone who would reason and seek to understand nature clearly and distinctly. To do that, however, such a person had to be anchored in his or her own mind; the work of natural philosophy required self-awareness—or, as Descartes put it, "I think therefore I am."

How to become the new kind of person who embraced his own clear and distinct ideas was the subject of Descartes' famous *Discourse on Method* (1637) (see Document 6). The tone taken throughout suggests humility and a willingness to address literate artisans, not just other masters of philosophy. Descartes was also deeply interested in anatomy and health in general, all subjects he pursued in conversation with Dutch doctors and colleagues. In turn, Dutch universities were among the first to teach his science, although not without enormous resistance from numerous faculty, both Protestant and Catholic, who remained Scholastics.[11]

Living as a Cartesian, inspired by Descartes' writings, could take many forms. Descartes' most innovative arguments centered on the human passions. Rather than moralize about and repress emotions, Descartes treated them as involuntary actions that simply are. Writers inspired by his vision turned to literature as the vehicle that could move the passions of the soul; art theorists urged a turn away from formalism toward a freer use of the brush, an attempt to evoke emotion and move the passions. Medical practitioners tried to understand the body, particularly pain, as the involuntary movement of atoms that put pressure on the tissues of the brain. All sought to better understand the mechanisms that united feeling with the senses, the mind with the body. Before Descartes, various schools of philosophy had urged the repression of emotion and the disciplining of sensual experience.

Cartesian understandings of nature were often taken up by thinkers far less pious than Descartes who could use Cartesian thinking to justify materialism—the belief that the world is nothing more than matter in motion, divorced from spirits and souls, even from divinity. Most of the leaders of the Scientific Revolution were devout Christians, but others, generally their readers or followers, sometimes used the new scientific ideas to embrace what the age called "deism" or "freethinking." Some in fact became atheists. By 1700, a coherent explanation of how the universe worked could be articulated without reference to God.

If nature is seen as Descartes saw it, composed of minuscule corpuscles, small and (for the most part) flexible particles, then surely these could be removed, leaving only vacant space. That is precisely what Robert Boyle (1627–1691) did with his air pump (see Document 7). No one would have predicted that this young aristocrat, the youngest son of the immensely wealthy Earl of Cork, born a Protestant in Ireland and destined for a life of leisure, travel, and the hunt, would turn himself into the model of the scientific work ethic and inspire an entire generation. But in the 1640s, Boyle experienced a religious conversion that brought him close to Puritanism, and he became an exceptionally devout Protestant. This happened at the moment when the English Parliament, led by the Puritans, had turned against King Charles I and the Anglican Church, and civil war raged in England, Ireland, and Scotland. Boyle also became a practicing alchemist, and reading alchemical texts turned him in the direction of atomism.[12]

Boyle's circle favored Parliament and the Puritan cause and, like so many on that side of the revolution then sweeping the country, Boyle believed that he lived in an unprecedented age of reformation. Learning would be transformed and the changes would bring about a new

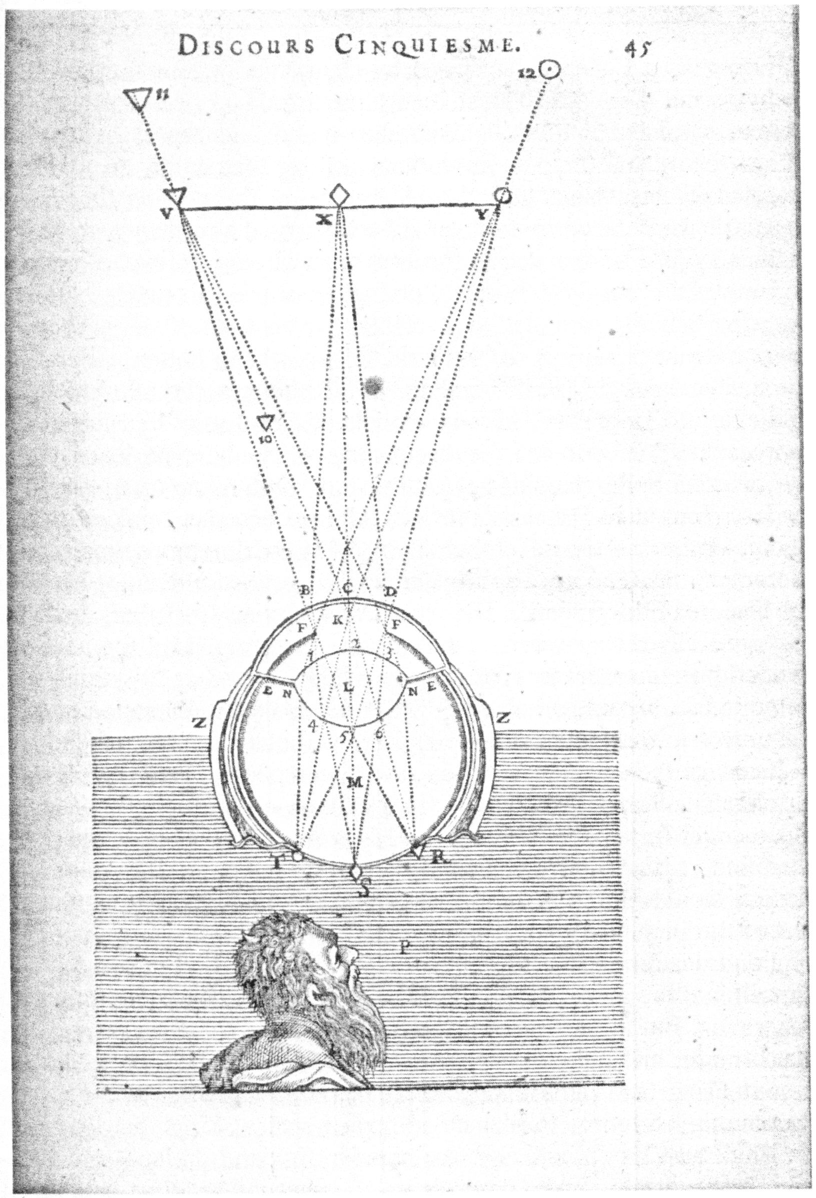

Figure 3. *René Descartes, Illustration of an Eye from* Discourse on Method, *1637.*

Here Descartes tries to illustrate the impact of light corpuscles on the eye, always traceable with mathematical precision.

Department of Special Collections, Charles E. Young Research Library, UCLA.

republic of learning and possibly foreshadow the arrival of a millennial paradise on earth. Christ would literally come again and institute a thousand-year reign of peace and prosperity. First Boyle laid out for himself an entire ethical system that turned away from privilege and birth, emphasizing good works and virtue. He then turned to alchemy and chemistry, and experimentation more generally. He used microscopes and, most importantly, sought a new philosophical anchor for his investigations. Boyle was guided in his early work by the alchemist and atomist, Daniel Sennert (1572–1637).

Deeply moved by Descartes and Sennert, Boyle united mechanical philosophy's assumptions with experimental protocol, essentially perfecting modern experimental techniques by insisting on replication and by describing his experiments in such minute detail that the results could be tested. In addition, as one of the founders of London's Royal Society, Boyle was a key player in the social organization of the new science. He saw himself as both a Baconian and a Cartesian, and he labored all his life to defeat Scholasticism. Unlike Descartes, Boyle sought not to make bold generalizations but to carefully amass information, replicate it, and offer it to the world as a tentative conclusion. He also took a posture of caution and invented a scientific style that was skeptical and attentive to detail. But when it came to what he called "philosophical theories," he firmly concluded, "If but a full light of experiments and observations be freely let in upon them, the beauty of those (delightful, but phantastical) structures does immediately vanish." The doctrine of form was one such theory.[13]

With Boyle's contributions to the experimental method, the characteristic features of modern science came clearly into focus. Nature consisted of material atoms; matter is weight and when subjected to pressure of another body, it moves. Boyle's ability to create a vacuum in a sealed glass jar, a device specially made for the purpose, proved the existence of air pressure or, as Boyle put it, the weight of the air. Men associated with Boyle's laboratory went on to invent some of the first steam engines that harnessed that weight by creating a vacuum in a cylinder. When filled with steam, it raised a beam, and, when turned into a vacuum by cold water evaporating the steam, it allowed the beam to fall. Mechanics, or what we generally call "mechanical engineering," was then put in place gradually, beginning late in the seventeenth century.

Boyle said that he had undertaken scientific work not only for the glory of God but also to show that modern learning had become superior to that of the ancients. To say that nature abhors a vacuum, as did

Aristotle, has the effect of endorsing what Boyle called "the vulgarly received notion of nature" (see Document 8). Boyle sought to defeat Aristotle as part of a larger project of removing the intellectual underpinnings of Catholic doctrine. He, like Bacon before him, believed that studying nature was a Protestant act of piety in the service of God. This vision of the purpose of science eventually became commonplace throughout Europe. In 1785 when the first scientific society for women opened its doors in the Dutch Republic, the lecturer of the day invoked these pious sentiments, what came to be called "physico-theology."

The mechanical philosophy was by no means the exclusive province of the wealthy and educated. Anthony van Leeuwenhoek (1632–1723) was the son of a basket maker who never attended a university. He represents one of the most remarkable aspects of the movement toward a new science—an artisan who became the discoverer of new worlds. Leeuwenhoek made his own microscopes. These microscopes were generally only about three inches long, and some may have magnified at five hundred times the size of the object. Only about nine have survived and one of those can magnify at two hundred seventy-five times. No one had an instrument as fine, and it was well over one hundred fifty years before microscopes would become more powerful.

With his powerful microscopes, Leeuwenhoek saw many things in nature for the first time. He observed the bacteria on his own teeth (see Document 9), the wings of flies, and the algae in ponds. He was methodical and endlessly patient, and he recorded his experiments in such a way that they could be replicated. When he could not read a work because it was not available in Dutch, he sought out translators. In short, he was a cosmopolitan, conversant with the latest microscopic work being done in Europe, and he was not afraid to disagree with other experimenters when he thought they had made an error. A small inheritance and a municipal position in his native town of Delft gave Leeuwenhoek the time to devote himself almost entirely to microscopic investigations. For his many achievements, he was made a Fellow of the Royal Society of London.

Leeuwenhoek's work bears a remarkable resemblance to that of his contemporary, the German-born artist and naturalist, Maria Sibylla Merian. Although Merian was a trained artist and Leeuwenhoek came from more humble origins, both were essentially artisans. They belonged to the class of investigators that historians have come to understand as absolutely fundamental to the social foundations of the

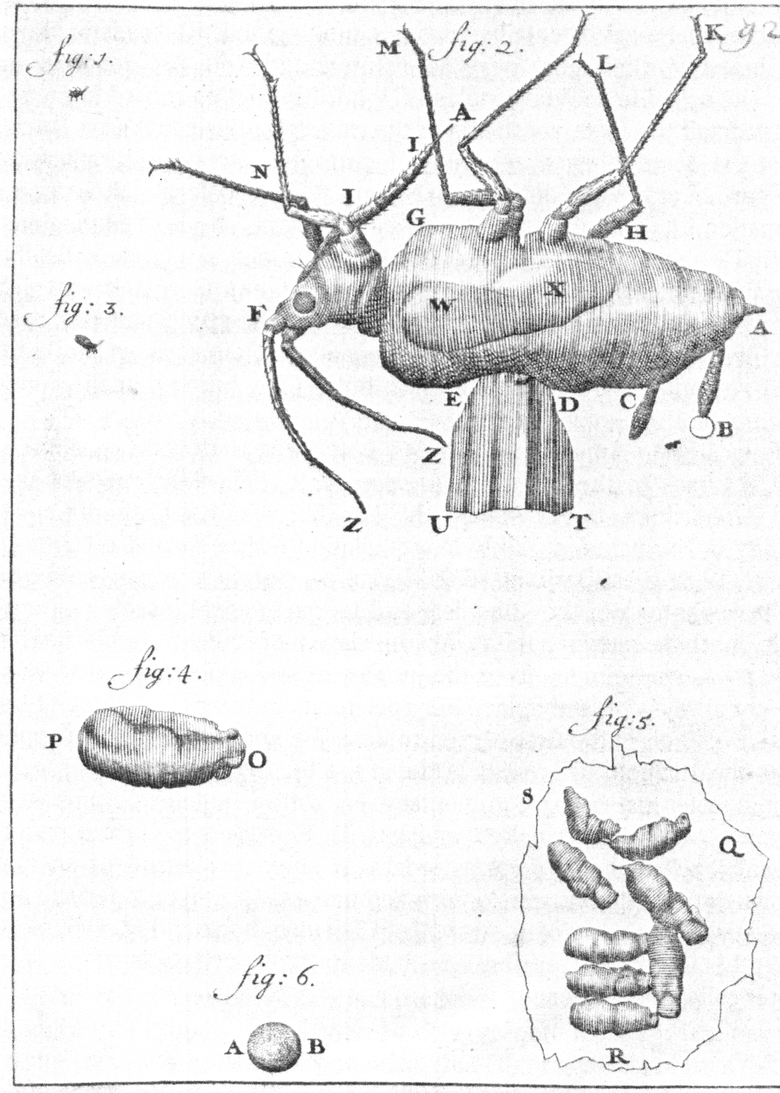

Figure 4. *Anthony van Leeuwenhoek, Illustration of a Flea, 1696.*
This engraving by van Leeuwenhoek illustrates the importance of pictures in conveying new natural philosophical knowledge.
Department of Special Collections, Charles E. Young Research Library, UCLA.

new science. Inspired by religion, Merian sought to know God's creation at a level of detail previously unimagined. Her artistic skills combined with immense personal courage and, with her daughter in tow, she sailed to see the jungles of South America to record in meticulous detail the metamorphosis of the insects of Suriname (see Document 14). Merian began her study of nature by catching caterpillars in her garden at the age of thirteen. She made watercolors of their transformation into butterflies and, just as important, she kept meticulous journals where she recorded everything that she saw systematically. Her father had been an engraver and a printer in Germany who did superb illustrations for alchemical works that he published. Her first two illustrated books written in German dealt with caterpillars and their remarkable transformation into butterflies, beetles, or flies (see Document 15).

Relocated to Amsterdam, Merian saw the many exotic specimens brought back by the Dutch trading companies. The religious sect she had joined there, the mystical Labadists, had also established a community in Suriname, possibly in expectation of the second coming of Christ. With great peril, in 1699 Merian set out on a voyage of six to eight weeks to join the Labadists and to see tropical insects and animals in their native habitat. Using slaves or native servants who brought her specimens from the jungles or sugar plantations, Merian did not always correctly place her specimens in the right "family." She was nevertheless the first person to describe and depict the pineapple in its own habitat, to present in detail the life cycle of the cockroach, and to offer extensive commentary on cotton, potatoes, yams and tomatoes, crocodiles, snakes, and lizards. She even brought a native woman back with her to Amsterdam as she was dependent on her knowledge of the indigenous flora and fauna. In so doing, Merian revolutionized the study of zoology. Both Leeuwenhoek and Merian alert us to the enormous contributions made by ordinary people to the new empirically based science.

NEWTONIAN SCIENCE

Bacon, Galileo, Kepler, Descartes, and Boyle all set the stage for the appearance of Newtonian science. Arguably the greatest mathematical and philosophical thinker of the Scientific Revolution, Isaac Newton (1642–1727) was born to neither luxury nor high learning. As a student at Cambridge University, he waited on tables. Forced to flee the town because of the appearance of bubonic plague in 1665, Newton found the time and solitude to develop his mathematical skills, to apply the new science of mechanics to the earth's motion, to investigate the nature of light, and to position himself—unknown at the time to anyone else—as the greatest living natural philosopher in the Western world. Cambridge gave him a professorship and there he remained until the early 1690s, when he went to London to become Master of the Mint.

Newton followed scores of original thinkers—as he put it, "I stand on the shoulders of giants." Boyle's vacuum was critically important for enabling Newton to break with Descartes' insistence that the heavens were filled with a fine material substance that swirled in vortices (as Descartes named them). Mechanically, the pressure they exerted on the planets held them in place. Newton accepted the mechanical vision of Galileo and Descartes and then radically transformed it when he applied it to the heavens. The mechanical philosophy insisted that all motions be caused by the impact of other bodies in motion, and hence denied that any invisible forces could act across a distance without the mediation of other bodies in motion, however ethereal they were. Newton, by contrast, demonstrated that all bodies evince an attraction to one another—a universal gravitation that he postulated took place across empty spaces. Newton presumed that universal gravitation worked in the vacuum of absolute space, in what he called "the sensorium" of God.

Newton's notebooks from his days at Cambridge University reveal not only his religious piety but also his intense study of the natural philosophers of the age. We tend to think of Newton as a great physicist—possibly the greatest before Albert Einstein. This is true, but it should not let us forget that he was also arguably one of the most powerful philosophical minds of the seventeenth century. Philosophical convictions, in particular a deep commitment to an atomic hypothesis, enabled Newton to embark on his optical experiments. He believed light to be composed of atomic particles (not waves) and thus he thought that it might be possible to disaggregate it. The prism experiments proved light to be a composite, that "light consists of rays differently refrangible." Each color would pass through a set of prisms at a different angle. Again, new experimental techniques put in place an orthodoxy that seemed to run against all observations. Sunlight had been regarded always as simple, homogeneous, and pure with colors being imagined as some sort of modification of sunlight. Newton argued that colors are "original and connate properties" of light. Colors appear when they are separated from sunlight; they are never created.

Indeed Newton's earliest publication, a paper sent to the Royal Society, was on color (see Document 10). In this paper on color, Newton never presented atomism. That theory served only as a hypothesis for Newton and as such remained unaddressed in his scientific writings. As he said repeatedly, "I do not feign hypotheses."

Not only did Newton embrace atomism, but he also acquired a belief in the power of invisible but knowable forces in nature. In the preface to the *Principia* (see Document 11), he called these forces "attractive or impulsive." These, he believed, had been known by the ancient philosophers, a wisdom that now could be recaptured because recent philosophers had "dismissed substantial forms and occult qualities." In the *Principia*, Newton put in place a rational as well as a practical mechanics. In the *Principia*, he grounded mechanics as well as celestial dynamics in geometry. In his subsequent works, however, Newton took mathematics a step further with the development of calculus. Newton's laws of force made possible a calculation as to the amount of work done by a certain volume of water falling from a known height, or the amount of work it would take to raise a certain weight a known distance. Thus, calculus provided a quicker and more flexible mathematics than geometry for describing bodies in motion.

Amid all the propositions and geometrical reasoning lies the centerpiece of the *Principia*: the establishment of universal gravitation and its use to demonstrate the elliptical orbits of the planets. In the first thirteen propositions of Book III, Newton derives the law of universal gravitation—that the planet is kept in its elliptical orbit because all bodies attract one another, a force that is inversely proportional to their distance from one another (according to their masses). The elliptical orbit results from the centripetal force pulling the planet toward the sun (or another planet). When accused of introducing an "occult force" into natural philosophy—because the action of gravity was through space at a distance—the second edition of the *Principia* shot back with the simple statement, "Gravity can by no means be called an occult cause . . . because it is plain from the phenomena that such a power does really exist." Newton further proclaimed that "the business of true philosophy is to derive the nature of things from causes truly existent." In answer to the question "What is gravity?" Newton said only that he had solely to prove mathematically that gravity operated throughout the universe, not to define it. Newton's method of reasoning about nature, going from an analysis by experimentation to a synthesis or general principle, to be tested again by analysis, became the methodological foundation of all scientific work.

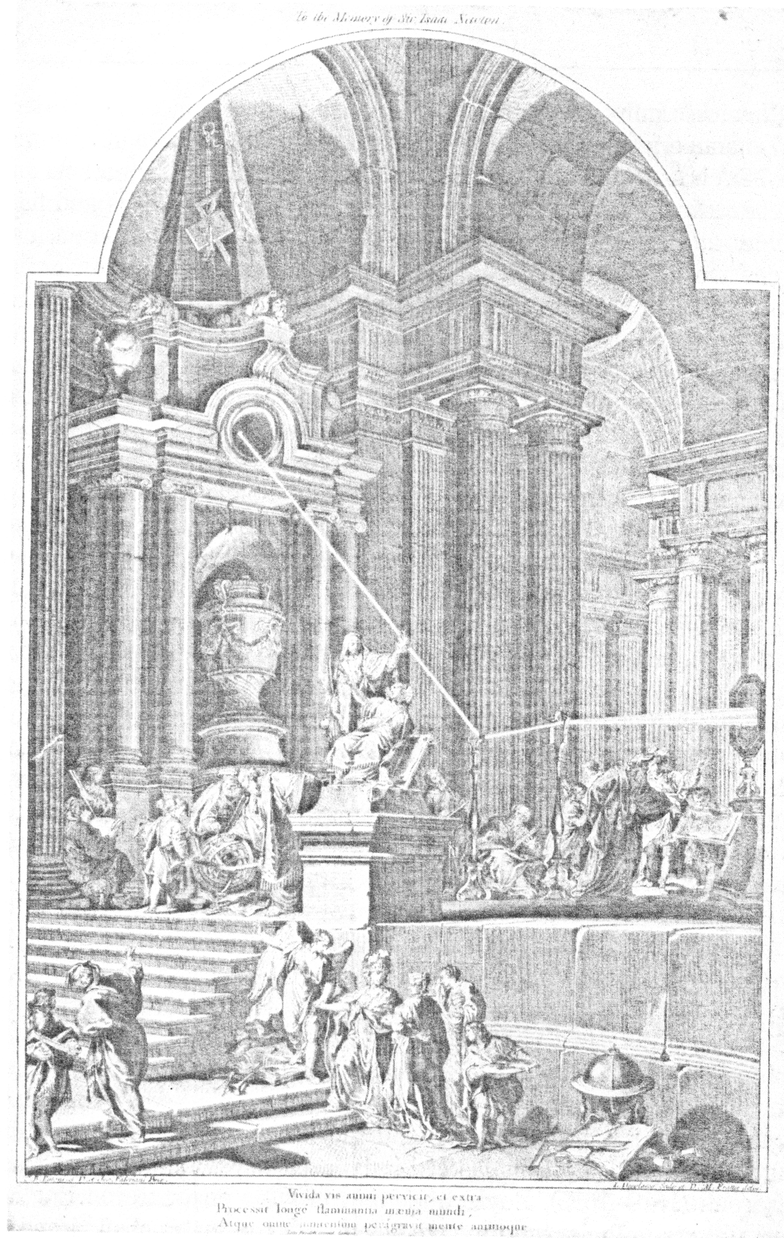

Figure 5. *Giovanni Battista Piton, "An Allegorical Monument to Sir Isaac Newton," 1741.*

Painted by Piton in 1741, the image is an apotheosis of Newton's great achievement in demonstrating the multiple rays that constitute "white light." The Fitzwilliam Museum.

Newton's universe was alive with invisible forces or, as he put it in one manuscript never published, "All nature is attended with signs of life." Such natural forces could make for chemical transformations and effect radical change. They were the source of earthquakes and tidal waves, and other dramatic changes visible in nature. These same forces worked on transforming ordinary substances. Newton was a practicing alchemist for most of his life, and he believed that some day someone truly adept would rearrange the atoms and succeed in transforming base metal into gold. Ironically, in the course of his alchemical work, best glimpsed through the *Thirty-first Query to the* OPTICKS (see Document 12), Newton put the science of chemistry on a firmer footing. He states his assumption in the form of a question at the opening of the thirty-first query, "Have not the small particles of bodies certain powers, virtues, or forces by which they act at a distance?" He believed that the new science would uncover those forces. When later in the eighteenth century European philosophers turned toward vitalism—a belief that life infused the material—they were developing hints found in the thirty-first query. For his achievements, Newton was awarded a knighthood and buried in Westminster Abbey. Artists also tried to demonstrate the majestic accomplishments of his optics. Poets sang, "Let Newton be, and all is light." Much of the adulation would have been lost on Newton, who paid little attention to either art or poetry. Something of a recluse, he never married and died in the home of his niece, leaving in the Bank of England the remarkable wealth of £14,000.[14]

RECONCILING SCIENCE, RELIGION, AND MAGIC

Bold and new ideas followed from the mechanical philosophy, but so too did new arguments for religion. Both Catholics and Protestants argued that the study of nature and the heavens reveals design, the hand of the deity as it instills order. Pious Protestants like Christiaan Huygens (1629–1695), Boyle, and Newton (who encountered English freethinkers in their own time) recoiled from the materialistic implications of the new science. They believed that science confirmed God's divine intervention into nature, not its ability to order itself. A science-supported Protestantism offered an alternative to both materialism and Catholicism, they insisted. As late as the 1780s, a Dutch scientific

society for women justified its existence by arguing that the study of nature was an act of piety; members started with lessons in mechanics. A hundred years earlier, Boyle saw that to defeat Scholasticism once and for all and to prove the mechanical philosophy definitively, results had to be visible, tangible, and replicable. But how to achieve them?

Over time, dozens of early modern contributors, both Catholic and Protestant, brought down the edifice of Scholasticism. Naturalists, alchemists, herbalists, physicians, armchair philosophers, anatomists, botanists, and mathematicians all had a hand in chipping away at the certainty that Aristotle and his Scholastic philosophers once imparted. Both astrology and alchemy played an important role in the beliefs of many early modern natural philosophers. For example, both Brahe and Kepler devoted a great deal of their time as astronomers and natural philosophers trying to improve astrology rather than discard it. At the same time, Kepler was a devoted Copernican.

That Brahe, Kepler, Galileo, and many other innovators of the new science all had legitimate interests in astrology—and there was nothing in the Aristotelian tradition that told them that having the stars influence human behavior was a bad idea—tells us that they were active courtiers, eager to work for their respective princes. Whether in Prague or Florence, courts expected advice that would potentially save them from ruinous decisions, and they thought that astrology might just give it. Similarly in its early years, the Paris Academy of Science, under court patronage from Louis XIV, pursued alchemy with much diligence. It promised improved pharmacology but also, at its most ambitious, the discovery of elixirs of life and even the transformation of base metals into gold. Princes like ordinary mortals aspired to great wealth and longevity, and they had the money to pay people to pursue both. Natural philosophers, in turn, quite often needed patronage to survive, especially in a world where the clergy and Scholastics controlled the universities. The Paris academy was eventually told by the king's representative to stop "the great work" of alchemy and get on with the business of mapping France. But in that year, 1685, Louis XIV had grand imperial plans to purge France of all Protestants and to expand French territory into the Low Countries. Safe in England, Boyle and Newton continued their alchemical pursuits privately, and it was only after 1700 that alchemy and astrology were firmly classified, where they remain today, as magical practices. The neat and clean distinctions we make between science and magic only impede our

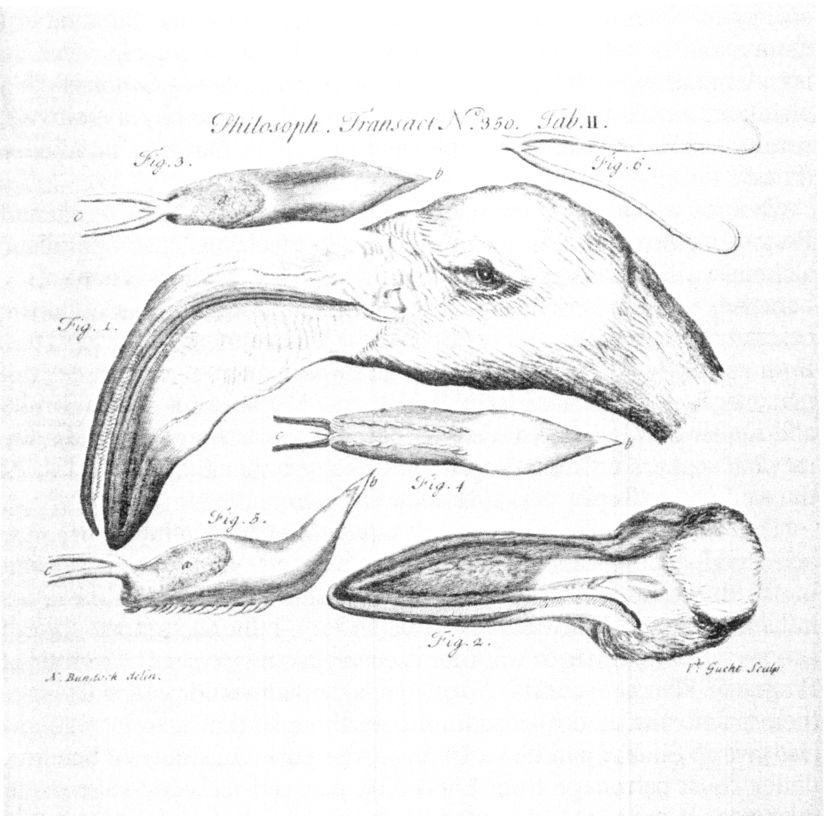

Figure 6. *James Douglas, M.D., Illustration of a Flamingo from* Philosophical Transactions of the Royal Society, *1714.*

This illustration appeared in the same volume of the *Philosophical Transactions of the Royal Society* as the description of diseases in oxen and cattle (Document 16). It brings together the world of imperial exploration and science.

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understanding of how early modern natural philosophers imagined nature. Similarly, laying emphasis on the great discoveries of early modern natural philosophy, as important as they were, can obscure the day-to-day interests of the many communities of naturalists. They could discuss agricultural topics or the weather with the same earnestness that they brought to astronomy or optics.

SPREADING THE SCIENTIFIC REVOLUTION

Even with the accomplishments of Galileo, Descartes, Boyle, Newton, and others, popular acceptance of the new science was slow to develop. When it did emerge, it sometimes took fanciful forms. The Dutch natural philosopher, Huygens, used the basic principles articulated by Descartes and, in a flight of imagination that was becoming increasingly frequent in Europe, gave the world a book that foreshadowed science fiction (see Document 13). In *The Celestial Worlds Discovered*, published in 1698, Huygens argued for the existence of life on other planets. If the planets are made of the same matter as the earth, why not inhabit them with the same creatures, human as well as animal? Huygens also used the occasion to champion the new science and to argue for European superiority. Many of the themes that inspired Huygens reappeared over the next few centuries. Some offered liberation and escapism, while others created an intellectual posture that contributed to Western imperialism. In Huygens's day, however, such fantasies were controversial—he willed the book to be published only after his death.

Nothing better indicates the character of day-to-day natural philosophical concerns than the proceedings of one of the many publications that appeared in Europe and eventually America, issued by one of the learned or scientific societies. The *Philosophical Transactions of the Royal Society*—still published today—began in 1665 (Document 16). It printed letters from the learned; the curious; the questioning; those seeking to be informative; and people concerned about epidemics and diseases, strange births, and finding longitude at sea. This journal concentrated on many of the breakthrough discoveries we associate with the Scientific Revolution. In the early modern period, day-to-day concerns about nature that aimed at being accurate, informative, and even original could concern anything and could come from anywhere in the literate world. In societies that were still deeply agricultural, matters that concerned the farm concerned everyone. The official publications of the scientific academies inspired a literature of popularization. Journals such as *The Ladies Diary* (1704–1774) never failed to publish mathematical puzzles and set riddles that required knowledge of natural phenomena. Simple mathematical questions were even set to rhyme: "At London one morning the Sun shining plain / The shadow I found the just length of my cane / As I held it upright; 'twas the tenth day of May, / Now tell me exactly the time of the day."[15]

Many of those who subscribed to such journals and encyclopedias also could be found in polite audiences that witnessed scientific demonstrations and lectures. Barely a town of any size existed in England and the Dutch Republic where such lectures could not be heard. In Newton's lifetime, his friend Jean T. Desaguliers (1683–1744) went everywhere in the English provinces, and on the Continent he spoke in French. His lectures on mechanics drew large audiences in capitals as well as in provincial towns (see Document 17). At the same time, Daniel Fahrenheit (of temperature fame; 1686–1736) not only made thermometers but also lectured on mechanics and optics throughout continental Europe. Outside of Paris, such lecturing was less commonplace in France than in England and Holland. By the 1780s, young manufacturers in towns like Birmingham, Leeds, and Manchester routinely went to lectures on mechanics and sought to apply what they learned to the manufacturing process. Desaguliers also did an English translation of a work by the leading continental follower of Newton, Willem Jacob s' Gravesande (1688–1742) (pronounced schgrav-san-de). This explication of Newtonian mechanics combined mathematics and machines, and with each published edition the machines came to predominate. By the 1790s, vast compendia of the arts and sciences illustrated every conceivable mechanical device and tool, while itinerant lecturers used them in tabletop demonstrations.

But what about the more obtuse ideas and writings that emerged from the Scientific Revolution? How could ordinary people come to understand them? We tend to think about the *Principia* today as largely a work in celestial dynamics. But that is not how contemporaries with practical interests read it—they saw it as a work in mechanics, in the science of local motion. However, few people actually read the book. It was—and is—extremely difficult to understand. Within Newton's lifetime, a small industry arose for the sole purpose of explaining the *Principia.* Dozens of textbooks appeared that broke the mechanics into manageable lessons, often illustrated with machines and not requiring mathematics. Lecturers took to the coffeehouses, halls, and demonstration rooms found not only in large cities such as London but also in every reasonably sized town throughout northern and western Europe. Selling Newtonian mechanics offered the possibility of a career to dozens of well-educated students of natural philosophy. Among the most famous of the first generation was Desaguliers, the official experimenter at the Royal Society of London.

No figure better represents the practical application of the Scientific Revolution than Desaguliers. Two years before Newton published his

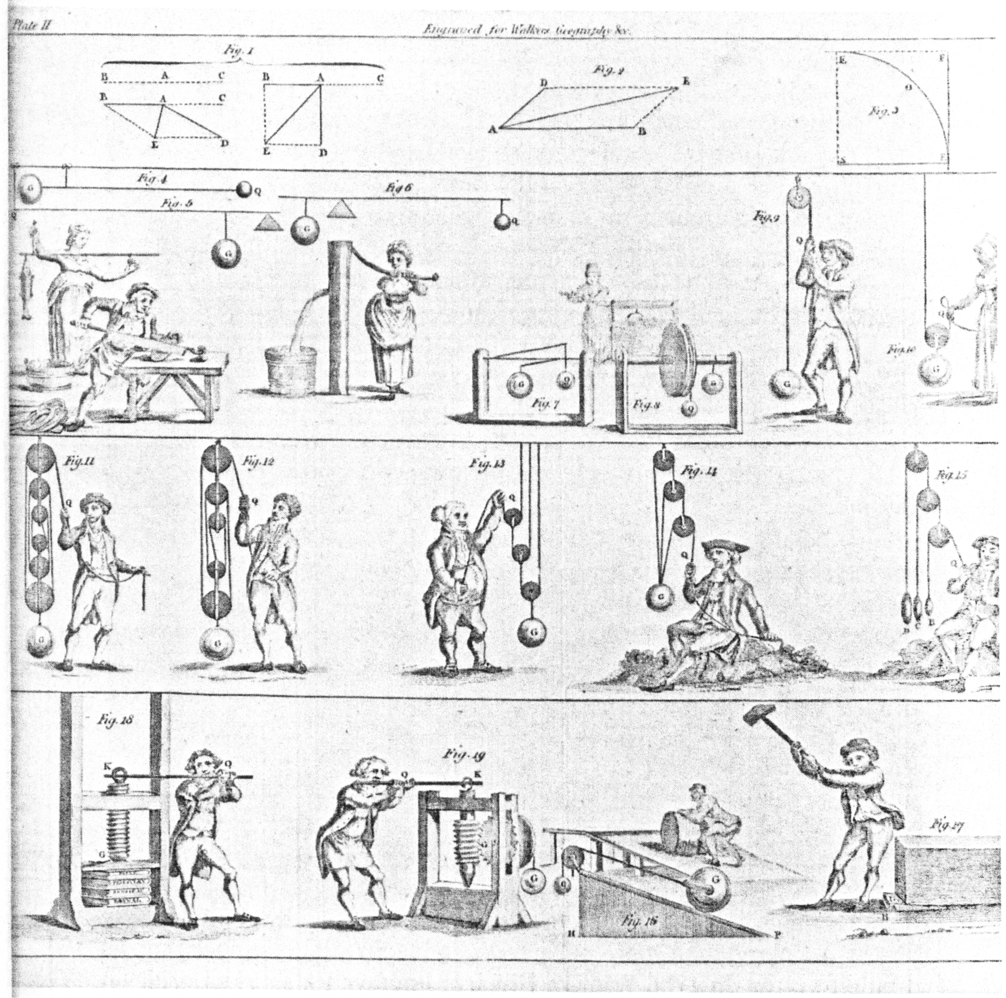

Figure 7. *John Walker, Various Mechanical Devices.*
Drawn on copperplate sometime in the mid- or late eighteenth century in Britain, the unsigned plate published by John Walker illustrates various methods for using levers, weights, and pulleys in work situations and preludes the increasing move toward industrialization.

Principia in 1687, King Louis XIV revoked the limited religious freedom enjoyed by Protestants in his kingdom. Over 150,000 refugees fled France and the Protestant Desaguliers and his parents were among them. After studying at Oxford and being ordained as an Anglican minister, Desaguliers became an avid experimenter and eventually a member of Newton's inner circle. Before anyone even invented the term, Desaguliers became a civil engineer. He worked on building projects, on the application of steam engines to mines and rivers, on the promotion and dissemination of labor-saving devices such as levers, weights, pulleys, and even simple steam engines. At the Royal Society, he performed electrical experiments and he further demonstrated the existence of the vacuum, a centerpiece of Newton's system of the world. He studied the chemical processes of repulsive and attractive forces, and he related both to the pervasiveness of electricity in nature. He became one of a handful of scientific lecturers who created the profession of the itinerant lecturer in natural philosophy. Desaguliers returned to the continent frequently, particularly the Dutch Republic, to lecture on Newtonian science. By 1790, it was possible for John Marshall, a Leeds manufacturer of linen cloth, to study the problems of resistance and velocity, and to learn about the working of steam engines, information he then took onto the factory floor as he sought to increase the speed of bobbins and harness the power of his new steam engines.[16]

Desaguliers illustrates the practical implications to be drawn from an intellectual revolution that in the first instance was conceptual and mathematical. His work in Newtonian mechanics points toward the Industrial Revolution that began first in Britain in the 1780s. Desaguliers was a new breed of civil engineer. He made his living not as a state servant, like most French engineers, but in the marketplace. He was also a clergyman more occupied as a mechanical engineer than as a pulpit orator. In 1736 William Hogarth engraved a satirical print on "The Sleeping Congregation." Desaguliers was widely said to be the preacher. He may have bored his congregations, but he knew the marketplace. The practical men to whom his text appealed were interested in building canals, moving coal out of mines, and manufacturing things more quickly and cheaply.

Benjamin Franklin (1706–1790) was a direct heir of Desaguliers's concern for utility and application. Indeed in the 1720s, when Franklin lived in London, his best friend was a lodger at the home of Desaguliers. Franklin's interests ranged from electricity, where he made original contributions by identifying positive and negative charges

Figure 8. *Portrait of Jean Desaguliers, 1743.*
Desaguliers was a new kind of clergyman who was also an engineer.
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(see Document 18), to heating stoves. He was an electrical experimenter who inflicted charges on himself to try to understand their strength. He pioneered bifocal glasses, founded state-of-the-art hospitals, and set up voluntary societies where people could hear about science or listen to lectures. He accepted the mechanical philosophy wholeheartedly and saw himself as engaged in solving problems bequeathed by Newton's observations in the *Thirty-first Query to the* OPTICKS. In his support for the new United States, Franklin turned his vision of scientific progress into serving the new republic. No area—from the gulf stream to shipping and navigation to manufacturing—escaped his attention. He became so famous that twenty thousand people attended his funeral in Philadelphia.

First in Britain by the 1780s and then in nineteenth-century continental Europe and North America, a new breed of mechanically and chemically educated entrepreneurs put engineers to work. Armed with the principles of Newtonian mechanics, together they built the first steam-powered factories. By the 1770s in coal fields near Newcastle in the north of England, one of the richest coal regions in Europe, there were over one hundred steam engines operating at ground level and below. This was at a time when no steam engines were used in French coal mines and only about a half dozen were present in the Belgian fields. Steam facilitated the dredging of harbors, the draining of swamps, the mining of coal, the weaving of raw cotton into cloth, and eventually the weaving of linen and wool. Just as had the natural philosophers before them, the engineers and entrepreneurs formed societies and offered lectures and demonstrations aimed first to make themselves, and then their skilled workers, scientifically literate. Through their efforts, steam power became a general-purpose technology that moved from mining and manufacturing to railroads and ships.

Whether at the royal courts or in one of the many formal and informal societies or academies that sprang to life under the impetus of natural inquiries, the practice of natural philosophy benefited enormously from social interactions. There was a small informal philosophical society around Galileo, and Huygens journeyed to Paris from the Dutch Republic to partake in the social life and patronage offered by the French academy. The founding of the *Accademia dei Lincei* in the early 1600s in Florence, the Royal Society in London in 1660, the *Académie des sciences* in Paris in 1666, and the Academy of Sciences in St. Petersburg, Russia, in 1725 establishes dates when strong interest in the new science took hold. Of all the seventeenth-century academies, perhaps the Royal Society of London became the most famous and prestigious. It was entirely private and depended on membership dues. Yet by the time Newton assumed its presidency, men from all over Europe and the American colonies aspired to be named Fellows,

and anyone who could put F.R.S. (Fellow of the Royal Society) after his name made a point of doing so.

When in the 1720s the king of Russia, Peter the Great, self-consciously sought to copy the behavior he had observed in Paris and London, science was already largely public, open, and increasingly cosmopolitan. Why did the intensely social configuration of the small society, composed of relative strangers, usually accompanied by some foreign members, become so integral to the growth of Western science? The example of Peter the Great helps to explain this. Peter saw such academies as "nothing if not a society [gathering] of persons who assist each other for the purpose of the carrying out of the sciences." Then, tellingly, he said that experiments needed to be verified in the presence of all members because "in some experiments many times one demands a complete demonstration from another, as, for example, an anatomist of the mechanic, etc." One person could not quite understand what another was trying to say without seeing it demonstrated. The complexity of the natural world required specialization and it, in turn, required social interaction among relative strangers to grasp what needed to be communicated. Thus, though the practice of science was often local, the frequent inclusion of international observers and contacts was also important for demonstrating scientific work.[17]

Something else also happened in these social settings. In the early modern period, habits were put in place that powerfully shaped the self-policing character of scientific inquiry. In effect, quite early in the formation of modern science and long before the creation of the modern laboratory, the doers of natural inquiry operated in groups that could conceivably include those who would become their most vigorous competitors and thus among their most attentive critics. As the late sociologist of science, Pierre Bourdieu, explained, such habits, once institutionalized, have come to mean that scientific work can be assessed through a shared process that aims toward the goal of greater rationality.[18] This cosmopolitan effect helped to set the self-examining character of science as we know it.

The very practices and languages of early modern science thus unwittingly played into the formation of a cosmopolitan experience, at least for men. The boundaries of natural inquiry, as distinct from other forms of learning, were fluid, disciplines were unformed, yet specialization existed. The fluidity of borders between the realms of each specialty—between mechanist and anatomist or between botanist and alchemist—led to social interaction, and so too did experimental demonstration. Inadvertently and slowly, within select groups where interest in nature dominated, cosmopolitan social manners and customs were invented and strengthened. National borders were crossed and, to some degree, social classes as well, because specialized knowledge was constantly being conveyed to those slightly less expert than the conveyor. Nothing was inherently cosmopolitan or open about the practitioners of science themselves. Indeed national rivalries, competition, and social nastiness were commonplace in early modern scientific circles. But natural inquiry, more than any other single new cultural phenomenon of the era—more than reading, or coffeehousing, or clubbing—constantly threw male strangers, and as we saw, a few female ones, into new and sustained social contact over problems that experience or experiments with nature presented. Long before the modern laboratory became inherent in scientific work, group experience, complete with differences bridged but rivalries also enhanced, had become commonplace. This was especially true when medical and alchemical topics came up for discussion. What could be more compelling than the challenge of trying to find medical cures, or the elixir of life, or speculating on the elusive practice of attempting to transmute base metals into gold? The alchemical quest required border crossing, and alchemy offers one of the keys to understanding the emergence of the cosmopolitan within the ethos of science.[19]

To be sure, many factors were at work in shaping a cosmopolitan ethos within early modern science. But if scientific work were to be expanded on, a common ideology and a common vocabulary about nature that could be shared across the borders of Europe were needed. By the mid-seventeenth century, there was no agreement as to what that vocabulary would be. Agreement emerged only gradually, generally by the 1690s. In the seventeenth century, a variety of philosophical languages and practices competed. One was derived from Aristotle and entrenched in the schools and universities. Another was alchemical and associated with a sixteenth-century doctor, Paracelsus (1493–1541), and flourished in private circles and at the courts. The ultimate victor in the struggle to establish a common vocabulary was deemed "mechanical" science and was associated with Galileo, Descartes, and Boyle. Their medium for communication and promotion included print culture, the new learned academies, and some courts. Gradually displacing "forms," "sympathies," or "tendencies" came new words—matter, motion, contact action, vacuum, and attraction. Understanding those terms had first been the privilege of men,

but by the mid-eighteenth century women had become consumers of mathematics and science, attending lectures and demonstrations, even forming their own scientific society.

CONCLUSION: THE LONG ROAD TO ACCEPTANCE

Aristotelian science was dethroned gradually. When the future architect of free-market economics Adam Smith (1723–1790) attended Oxford University in 1740, he was horrified to find that in philosophical matters the curriculum was still heavily Aristotelian. His own university in Glasgow was more philosophically modern and he would have had more of an intellectual feast at Cambridge, where Newton had taught and where the new science and its natural philosophy had been ensconced. Had Smith crossed the channel and ventured to the Sorbonne in Paris, he would have also found Aristotle alive and well in the curriculum, with only Descartes offering a serious challenge.

In France, Newtonian science only made deep inroads in the academies after 1750 and largely because, as one scholar puts it, "If Newton finally triumphed in France it was probably over the corpse of the Jesuit Order." In other words, Jesuit teachers who controlled the majority of French colleges had just gotten to the point of embracing Descartes; Newton was just too much to ask. In the 1760s, for a variety of complex political reasons, the Jesuits were expelled from France. The curricula of the schools and universities decisively shifted and the new science, in its Newtonian form, became commonplace although atomism was still controversial at the beginning of the French Revolution in 1789.[20]

As we watch the negative reaction to science in some religious quarters today, we might think about the achievements of the seventeenth and eighteenth centuries. Within deeply Christian Europe, a new understanding of nature unfolded—not without opposition, particularly among Scholastics—and it valorized the empirical, the experimental, the mathematical, and the mechanical. Banished were notions of hidden, unknowable forces in nature, spirits, and demons. Mathematics had once been seen as a practical tool, not the province of philosophers. By the late seventeenth century, it had come to be relevant to everything from predicting life expectancy to calibrating machines. These changes coincided with the discovery of new peoples and continents, which in turn suggested that ancient learning, even recent learning, had to be improved. Religious conflict and intolerance also suggested that new sources of knowledge and authority were urgently needed. Gradually, rationalism and empiricism came to displace tradition and religious dogmatism, and, as a result, modern industrial societies emerged. The new scientific culture when combined with the profit motive and power technology brought into being the industrial age. Its wealth and power turned the West into an imperial and for a time the hegemonic power on our planet.[21]

NOTES

[1]José de Acosta, *Natural and Moral History of the Indies*, trans. Frances M. López-Morillas (Durham, N.C.: Duke University Press, 2002), 20–21.

[2]See Richard G. Lipsey, "Economic Growth Related to Mutually Interdependent Institutions and Technology," http://www.econ.sfu.ca/research/RePEc/sfu/sfudps/dp08-03.pdf. For the quotation comparing Europe with the East, see Jack Goldstone, *Why Europe? The Rise of the West in World History* (New York: McGraw-Hill, 2009), 20. The notion of the paradigm shift belongs to Thomas Kuhn, *The Structure of Scientific Revolutions* (Chicago: University of Chicago Press, 1962). For the various approaches taken to the question, see Steven Shapin, who dwells on Robert Boyle and also argues that there really was no scientific revolution, in his *The Scientific Revolution* (Chicago: University of Chicago Press, 1996); for Betty Jo Dobbs and alchemy, see the essay by her and others in Margaret Osler, ed., *Rethinking the Scientific Revolution* (Cambridge: Cambridge University Press, 2000). For the founding of the university and science at Berlin, see Thomas Albert Howard, *Protestant Theology and the Making of the Modern German University* (Oxford: Oxford University Press, 2006), chap. 3. For the importance of patronage, see Paul A. David, "The Historical Origins of 'Open Science': An Essay on Patronage, Reputation and Common Agency Contracting in the Scientific Revolution," *Capitalism and Society* 3, no. 2 (2008): article 5 For Aristotle, I used *Physics*, trans. Robin Waterfield (New York: Oxford University Press, 1996).

[3]Brian P. Copenhaver and Charles B. Schmidt, *Renaissance Philosophy* (New York: Oxford University Press, 1992).

[4]Francis Suarez, *On the Formal Cause of Substance: Metaphysical Disputation XV*, trans. John Kronen and Jeremiah Reedy; introduction and explanatory notes by John Kronen (Milwaukee: Marquette University Press, 2000), 17–19.

[5]For scholarship on the process of imperial expansion as experienced by the Dutch, see Harold J. Cook, *Matters of Exchange: Commerce, Medicine, and Science in the Dutch Golden Age* (New Haven, Conn.: Yale University Press, 2007). Also quite interesting are Anne Goldgar, *Tulipmania: Money, Honor, and Knowledge in the Dutch Golden Age* (Chicago: University of Chicago Press, 2007), and Julia Adams, *The Familial State: Ruling Families and Merchant Capitalism in Early Modern Europe* (Ithaca, N.Y.: Cornell University Press, 2005). For a fresh and suitably harsh look at the nature of Dutch imperialism in the period and its impact on the visual arts, see Julie Berger Hochstrasser,

Still Life and Trade in the Dutch Golden Age (New Haven, Conn.: Yale University Press, 2007). See also Antonio Barrera-Osorio, *Experiencing Nature: The Spanish American Empire and the Early Scientific Revolution* (Austin: University of Texas Press, 2006); Miguel de Asúa and Roger French, *A New World of Animals: Early Modern Europeans on the Creatures of Iberian America* (Burlington, Vt.: Ashgate, 2005); and, on the new mathematics, see Amir Alexander, *Geometrical Landscapes: The Voyages of Discovery and the Transformation of Mathematical Practice* (Stanford, Calif.: Stanford University Press, 2002). In general, see Joan-Paul Rubiés, *Travel and Ethnology in the Renaissance: South India through European Eyes, 1250–1625* (Cambridge: Cambridge University Press, 2000). And see Francis Bacon, *The New Organon*, ed. Lisa Jardine and Michael Silverthorne (Cambridge: Cambridge University Press, 2000), 93.

[6]Deborah E. Harkness, *The Jewel House: Elizabethan London and the Scientific Revolution* (New Haven, Conn.: Yale University Press, 2007).

[7]Quoted in Jean Dietz Moss, *Novelties in the Heavens: Rhetoric and Science in the Copernican Controversy* (Chicago: University of Chicago Press, 1993), 33.

[8]*Réimpression de l'Ancien Moniteur*, t. 29, 1847, 402–3. Number 1, reprinting the speech given by François de Neufchâteau on 1 Vendémiaire, Year 7, September 26, 1798.

[9]Laura Fermi and Gilberto Bernardini, *Galileo and the Scientific Revolution* (Mineola, N.Y.: Dover Publications, 2003), 85–86.

[10]Scriptural verses relevant to Galileo's trial (from the King James Version of the Bible and the Douay/Rheims Catholic Bible):

Joshua 10 (Verse 13)
[King James Bible]
And the sun stood still, and the moon stayed, until the people had avenged themselves upon their enemies. Is not this written in the book of Jasher? **So the sun stood still in the midst of heaven,** and hasted not to go down about a whole day.

[Catholic Bible]
13 And the sun and the moon stood still, till the people revenged themselves of their enemies. Is not this written in *the book of the just?* **So the sun stood still in the midst of heaven**, and hasted not to go down the space of one day.

Psalm 19 (Verses 1–5)
[King James Bible]
1 The heavens declare the glory of God; and **the firmament sheweth his handywork**.
2 Day unto day uttereth speech, and night unto night sheweth knowledge.
3 There is no speech nor language, where their voice is not heard.
4 Their line is gone out through all the earth, and their words to the end of the world. **In them hath he set a tabernacle for the sun,**
5 **Which is as a bridegroom coming out of his chamber**, and rejoiceth as a strong man to run a race.

Psalm 104 (Verses 1–5)
[King James Bible]
1 Bless the LORD, O my soul. O LORD my God, thou art very great; thou art clothed with honour and majesty.
2 Who coverest thyself with light as with a garment: who stretchest out the heavens like a curtain:
3 Who layeth the beams of his chambers in the waters: who maketh the clouds his chariot: who walketh upon the wings of the wind:
4 Who maketh his angels spirits; his ministers a flaming fire:
5 **Who laid the foundations of the earth, that it should not be removed for ever.**

Isaiah 40 (Verse 22)
[King James Bible]
22 **It is he that sitteth upon the circle of the earth**, and the inhabitants thereof are as grasshoppers; **that stretcheth out the heavens as a curtain, and spreadeth them out as a tent to dwell in**.

[Catholic Bible]
22 It is he that sitteth upon the globe of the earth, and the inhabitants thereof are as locusts: **he that stretcheth out the heavens as nothing, and spreadeth them out as a tent to dwell in**.

A decree of February 19, 1616, summoned Qualifiers of the Holy Office and required them to give their opinion on the two following propositions in Galileo's work on the solar spots. (The assessment was made in Rome, on Wednesday, February 24, 1616.)

Proposition to be assessed:

(1) The sun is the center of the world and wholly immovable from its place.
Assessment: This proposition was unanimously declared "foolish and absurd. philosophically and formally heretical inasmuch as it expressly contradicts the doctrine of the Holy Scripture in many passages, both in their literal meaning and according to the general interpretation of the Holy Fathers and the doctors of theology."
(2) The earth is not the center of the world, nor immovable, but it moves as a whole, also with diurnal motion.
Assessment: This proposition was unanimously declared "deserving of the like censure in philosophy, and as regards theological truth, to be at least erroneous in faith."

[11]Maarten Prak, *The Dutch Republic in the Seventeenth Century* (Cambridge: Cambridge University Press, 2005), 228–31.
[12]William R. Newman, *Atoms and Alchemy: Chymistry and the Experimental Origins of the Scientific Revolution* (Chicago: University of Chicago Press, 2006).
[13]Robert Boyle, *Certain Physiological Essays and Other Tracts . . .* (London: Henry Herringman, 1669), 8.
[14]For Newton's bank records, see Bank of England Archives, London, AC 27/444 Bank Stock Number 21 I-Q Anno 1725–1732, Folio 1105, May 18, 1727, Sir Isaac Newton deceased and with distribution of £1,750 to each of eight people.
[15]*The Ladies Diary* (London: n.p., 1713), Question 30 by A.W.
[16]For the comings and goings of Desaguliers in Whig circles, see British Library MSS ADD 61999 January 1716/17 diary Henry Brydges, second son of Duke of Chandos, vicar at Amersham, Bucks, f. 22 et. seq. On Marshall, see Margaret C. Jacob, "Mechanical Science on the Factory Floor: The Early Industrial Revolution in Leeds," *History of Science* 45 (June 2007): 197–221.
[17]Michael D. Gordin, "The Importance of Being Earnest: The Early St. Petersburg Academy of Sciences," *Isis* 91 (2000): 10.
[18]Pierre Bourdieu, *Science of Science and Reflectivity*, trans. R. Nice (Cambridge: Polity, 2004).
[19]See chapter 2 in Margaret C. Jacob, *Strangers Nowhere in the World: The Rise of Early Modern Cosmopolitanism* (Philadelphia: University of Pennsylvania Press, 2007).
[20]L. W. B. Brockliss, *French Higher Education in the Seventeenth and Eighteenth Centuries: A Cultural History* (Oxford: Oxford University Press, 1987), 366.
[21]Joel Mokyr, *The Gifts of Athena: Historical Origins of the Knowledge Economy* (Princeton, N.J.: Princeton University Press, 2002); also, his "The Intellectual Origins of

Modern Economic Growth," *Journal of Economic History* 45 (2005): 285–351, and his *The Enlightened Economy* (New Haven, Conn.: Yale University Press, 2009). See also http://industrialization.ats.ucla.edu.