■ THINKING HISTORICALLY

Distinguishing Change from Revolution

The world is always changing; it always has been changing. Sometimes, however, the change seems so formidable, extensive, important, or quick that we use the term *revolution*. In fact, we will use the term in this and the next two chapters. In this chapter we will examine what historians call the scientific revolution. The next chapter will deal with political revolutions and the chapter following with the industrial revolution. In each of these cases there are some historians who object that the changes were not really revolutionary, that they were more gradual or limited. Thus, we ask the question, how do we distinguish between mere change and revolutionary change?

In this chapter you will be asked, how revolutionary were the changes that are often called the scientific revolution? The point, however, is not to get your vote, pro or con, but to get you to think about how you might answer such a question. Do we, for instance, compare "the before" with "the after" and then somehow divide by the time it took to get from one to the other? Do we look at what people said at the time about how things were changing? Are we gauging speed of change or extent of change? What makes things change at different speeds? What constitutes a revolution?

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Why Europe? 2009

This selection is drawn from a book by a modern historian who asks one of the enduring questions of modern history: Why was it that people in Europe pioneered the breakthroughs in modern scientific thought in the seventeenth century that led to an industrial revolution? This is a particularly intriguing question when you realize, as Goldstone points out, that between 1000 and 1500 China, India, and the Muslim world made far greater strides in science than Europe. What were the obstacles to advancement in scientific thought in most societies before 1500? What happened in Europe between 1500 and 1650 to change the way people thought about

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Source: Jack Goldstone, *Why Europe? The Rise of the West in World History 1500–1850* (New York: McGraw-Hill, 2009), 144–53.

nature, and how did that thinking change? How did rationalism and empiricism change European science after 1650? How does a combination of rationalism and empiricism produce better science than either separately or than the other two sources of authority: tradition and religion?

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Goldstone does not use the term *scientific revolution* in this selection, but he discusses a number of changes in European society, politics, and beliefs that might be called revolutionary. What are these changes? What would make them revolutionary changes? Is it a matter of how fast they occurred, how widespread they were, what impact they had, or how unusual or uniquely European they were? Which of these measures makes them more revolutionary?

One must ask, given the glorious achievements of Islamic and ot scientific traditions that were sustained over many centuries: Why d they not develop the same kind of advances leading to industrializati as did the modern European sciences?

Varieties of World Science and Different Approaches to Understanding Nature

Approaches to natural science varied across time and across differe civilizations. Some traditions, such as that of China, made enormo advances in herbal medicine but remained weak in basic anatomy. Oth traditions, like that of the Mayan Indians of Central America, we extremely accurate in observational astronomy but very weak in phys and chemistry.

Nonetheless, most premodern scientific traditions shared severa common elements. First, their scientific understanding of nature was ge erally embedded in the framework for understanding the universe la out in their society's major religious or philosophical traditions. Althoug there was potential for great conflict if scientific studies of nature sho contradict elements of religion, this was usually avoided by making th religious views dominant, so that scientific findings would have to b reconciled with or subordinated to religious beliefs. This does *not* me that religions were opposed to science—quite the opposite! Most poli cal and religious leaders sponsored both scientific and religious studie believing that each supported the other. Many distinguished Confuci scholars, Islamic judges, and Catholic priests were also outstandi mathematicians and scientists. For the most part, detailed observati of nature, including accurate measurements of planetary motions and natural phenomena, were considered valuable as privileged knowledge to political and religious elites or socially useful for improving architecture, farming, and medicine.

However, science generally remained intermingled with religious and philosophical beliefs, and any inconsistencies were generally resolved in favor of preserving the established religion. This meant that truly novel work risked being suppressed by political and religious authorities, especially during periods of religious conservatism or state enforcement of orthodox religious views.

Second, most premodern sciences maintained a separation between mathematics and natural philosophy (the study of nature). Mathematics was considered useful for exploring the properties of numbers (arithmetic) and relationships in space (geometry). It was also useful for a host of practical problems, such as surveying; compiling tables of planetary positions in the skies for navigation, calendars, and astrology; and accounting. But most premodern scientific traditions—including those of the ancient Greeks, medieval Europeans, Arabs, and the Chinese—held that mathematics was *not* useful for studying the basic constitution of the universe. This was the main subject matter of natural philosophy (the study of the natural world) and theology (the study of religious texts, including the relationship of humans and the natural world to the Creator).

If one wanted to know the nature of God or the soul, or the relations between humankind and God, or the purpose of animals, or the nature of the stuff that composed the world—plants, stones, fire, air, liquids, gases, crystals—well, these were problems for reasoning based on experience and logic, not on mathematical equations. The task of philosophy was to comprehend the essential nature of things and their relationships. Measurement was a practical matter, useful but best left to surveyors, tradespeople, moneylenders, and other practical folks.

Thus the Chinese and Indian traditions believed in a basic hidden force of nature—*qi* in China and *prana* in India—that animated and infused the world. For Chinese scientists, the world was always changing, and these changes formed complex cycles and flows of opposing forces that operated to maintain an overall harmony. Thus despite their enormous skill and use of detailed mathematics and observation in areas from canals and irrigation works to astronomy and clocks, it never occurred to orthodox Chinese scientists to regard the universe as a mechanical clockwork or to apply mathematical equations to understand why natural processes occurred. What mattered was understanding signs of the ever-shifting flows of *qi* between opposing conditions—*yin* and *yang*—to avoid excesses and to maintain the harmony of the whole.

The Greeks too, since the time of Aristotle, similarly maintained a separation of mathematics from natural philosophy. Aristotle's philosophy of nature, which by the Middle Ages had become the dominant na philosophy in Europe, analyzed nature by identifying the basic ele that composed all things. For Aristotle, there were four b elements—earth, fire, air, and water—which were defined in terms of they behaved. Things made of earth are solid and naturally tend to fa the center of the universe, which is why the solid earth beneath us con of a sphere, and all solid things fall toward it. Fire naturally rises, so th infused with fire rise. Air is transparent and moves across the surface o Earth as winds; water flows and moves in currents and puddles and fill seas and oceans. Since the Moon and Sun and stars and planets ne move up nor down but remain in the heavens, moving in circles in skies, they must be composed of yet another, distinct element that was fect and unchanging, which the Greeks called the "aether."

The way these principles were discovered and proved was thro logic and argument based on experience, not through mathema Although mathematical forms and principles could help identify a measure relationships in nature, the true "essence" of reality was se philosophy. For example, even though the planets actually move at va ing speeds in elliptical orbits around the Sun, for over 1,000 ye Islamic and European astronomers sought to describe their orbits so in terms of combinations of uniform and circular motions, beca Aristotle's natural philosophy had decreed that this was the only w that heavenly bodies could move.

In the Middle Ages, European scholars continued to treat mat matics as mainly a practical field, while focusing their attention on lo and argument as the keys to advancing knowledge. Although medie scholars in Europe did make significant advances in the study of mo and absorbed much of the critical commentary on Greek science a philosophy from the Islamic world, they did not reject or replace th major tenets of classical Greek science or their own religious theolo Rather, much of the effort of European thought in the Middle Ages co sisted of efforts to reconcile and synthesize the writings of the Gre authors on science and politics with the precepts of the Christian Bi and other religious texts, culminating in the work of St. Thom Aquinas.

The Islamic scientific tradition went further than any other in us experiments and mathematical reasoning to challenge the arguments Ptolemy, Galen, and others of the ancient Greeks, creating new advan in medicine, chemistry, physics, and astronomy. Yet within Islam, discussion of the fundamental relationships and characteristics of na was separated into the teachings of the Islamic sciences, based on cla cal religious texts, and the teachings of the foreign sciences, including the works of Greek and Indian authors. After the writings of the ph sophical critic Al-Ghazali in the eleventh century, who championed value of the Islamic sciences on truly fundamental issues, this divi generally maintained, and even the most remarkable advances and findings with regard to revisions of Greek learning were not permitted to challenge the fundamental views of the universe as expressed in Islamic religious works.

Thus in all the major scientific traditions, whereas precise measurement and sophisticated mathematics were widely used, mathematical reasoning was not used to challenge the fundamental understanding of nature that was expressed in natural philosophy and religious thought.

Third, in most places, the dominant assumptions and traditions of science were so distinctive and so well established that they could hardly be shaken even by encounters with different notions and ideas. These scientific traditions tended to grow incrementally, with each successive generation modifying yet building on the works of their predecessors, so that over time a rich and longstanding tradition of scientific methods and findings grew up, intertwined with an established religious tradition. These structures of thought tended to resist wholesale change or replacement and to marginalize heterodox or conflicting views.

Thus by 1500, there were many different varieties of science in the world, each with their own strengths and distinctive characteristics. Most had developed precise observations of the Earth and heavens and had systematized a great number and variety of discoveries about nature. Most had developed a classification of essential relationships or characteristics of natural things. Most were linked in some fashion to one of the great axial age religions and over many centuries had worked to accumulate knowledge while building frameworks that were compatible with those religions. And in the next century or two, most scientific traditions would be driven to greater subordination to classical and religious orthodoxy by rulers who were responding to the political and social conflicts that struck over almost all of Europe and Asia.

How then was it possible that any culture could develop . . . technical innovations, based on new instruments and mathematical natural science . . . ? To understand this, we have to grasp the unusual events and discoveries that led to unexpected changes in Europe's approach to science.

Europe's Unusual Trajectory: From Embracing to Escaping Its Classical Tradition, 1500–1650

The study of ancient schools of thought was given a new direction by the realization, by the early 1500s, that the Spanish voyages to the west had discovered not just an alternate route to India, but in fact a whole new continent, a "New World" unknown to ancient geographers and scientists. Navigators came to realize that practically all of Greek geography was badly mistaken. Also in the early 1500s, the research of the Belgi anatomist Andreas Vesalius (who was building on the prior work Arab scholars) demonstrated to Europeans that Galen's knowledge human anatomy was, in many respects, inaccurate or deficient beca it was based on deductions from animal dissections rather than empirical study of human cadavers. Vesalius showed that many Galen's (and Aristotle's) statements about the heart, the liver, the blood vesse and the skeleton were wrong.

Then in 1543, Copernicus published his new methods for calcul ing the movements of the planets based on a solar system with a movi Earth circling the Sun. Although some supporters, trying to avoid co flict with the church, argued that his work should only be taken as a ne method of predicting planetary positions, Copernicus argued qu forcefully that the structure and dynamics of the solar system made mo sense, logically and aesthetically, if the Earth and all other planets re volved around the Sun. If so, then the system of Ptolemy and Aristot with the Earth as the center of all motion, was in error.

In 1573, the Danish astronomer Tycho Brahe published his accou of the supernova that had suddenly appeared near the constellation Cassiopeia in 1572. This was a phenomenon that had never be recorded in European astronomy. Indeed, since the time of Aristotle, was assumed that the skies were unchanging and constant in their pe fection. Comets and meteors were known, of course, but they were co sidered weather phenomena, like lightning that occurred close to th Earth rather than in the celestial heavens. But the supernova was no comet or meteorite, because it showed no motion: It was a new bod that behaved like a fixed star—something that was, according Aristotle's philosophy, impossible.

Five years later, Brahe showed by careful observation of the mov ments of the great comet of 1577 that this comet must be farther aw from the Earth than the Moon and thus was moving through the celes heavens, not the atmosphere, striking yet another blow against Aristot cosmic system. Supernovae that can be observed from Earth by naked eye are rare, but as chance would have it, in 1604, yet anoth supernova made its appearance, thus showing conclusively that heavens were not unchanging after all.

By the late 1500s and early 1600s, therefore, the wisdom of Aristot Galen, and Ptolemy, which had been accepted for over 1,000 years, coming under widespread attack. European scholars sought out observations and new instruments for studying nature that could determine who was correct, or incorrect, in their description of natu and the universe.

In 1609, Galileo used the new spyglass or telescope—invented Dutch lens-grinders and then improved by Galileo himself—to obse the heavens. Looking at the Moon through a telescope rather than the unaided eye, Galileo saw what looked like giant mountains and craters on the surface, which through the telescope looked positively Earth-like. Jupiter was found to have its own moons circling it, implying that the Earth could not be the center of all celestial motions. In every direction were previously unknown stars, and even the Milky Way was revealed to consist of thousands of tiny stars. Though many critics at first dismissed the views through the telescope as false magic, enough people acquired their own telescopes and confirmed Galileo's discoveries that they were widely accepted. People came to realize that the universe in which they lived was nothing like that described by the ancient Greek authorities.

Copernicus was not the first astronomer to suggest that the Earth revolved on its axis and moved around the Sun, instead of being the fixed center of the universe; a few ancient Greek and Islamic astronomers had also suggested that this was possible. However, until telescopic observations of the moons of Jupiter demonstrated the fact of motion around a body other than the Earth, there was no evidence on which to base a successful overthrow of Aristotle's views. It was only after 1600, with so many new observations that contradicted the ancient Greeks' knowledge—of geography, of anatomy, and of astronomy—piling up in all directions, that it became possible, even imperative, to adopt alternatives to Aristotle in particular and to Greek science and philosophy as a whole.

From 1600 to 1638, a series of books presenting new knowledge or proclaiming the need for a "new science" made a compelling case that the knowledge of the ancients was seriously flawed.

1600: William Gilbert, *On the Magnet*
1620: Francis Bacon, *The New Organon, or True Directions*
  Concerning the Interpretation of Nature
1620: Johannes Kepler, *The New Astronomy*
1626: Francis Bacon, *The New Atlantis*
1628: William Harvey, *On the Motion of the Heart and Blood*
1638: Galileo, *Discourses on Two New Sciences*

Gilbert argued that compass needles pointed north because the whole Earth acted as a giant magnet. Francis Bacon argued that Aristotle's purely deductive logic (collected under the title *Organon*—which means "instrument or tool") could not be trusted as a guide to understanding nature; instead Bacon argued for the use of inductive logic, based on a program of experiment and observation, as a superior method for discovering knowledge of the world. Kepler showed that the planets actually traveled in elliptical orbits around the sun, not in circles. And William Harvey showed that, contrary to Galen's teachings, the supposedly separate veins and arteries were in fact one system through which the blood was circulated by the beating of the heart.

By the mid-1600s, therefore, European philosophers and scientists found themselves in a world where the authority of ancient texts was clearly no longer a secure foundation for knowledge. Other major civilizations did not suffer such blows. For the Chinese, Indians, and Muslims—accustomed to operating in a vast intercontinental trade sphere from China to Europe and generally seeing themselves at the center of all that mattered—the discovery of new, lightly peopled lands far to the west made little difference. But for Europeans—who had long seen themselves on the literal edge of the civilized world with all that mattered lying to the east—the discovery of new and wholly unknown lands to the west changed their fundamental position in the world.

Similarly, Chinese and Indian astronomers had observed supernovae before (accurately recording observations of the heavens for thousands of years) and had long ago developed philosophies of nature that were built around ideas of continuous change as the normal course of things in the universe. Unlike the Greeks and Europeans, they had no rigid notions of perfect and unchanging heavens, separate from the Earth, that would cause their classical traditions to be fundamentally challenged by new observations of comets and stars.

Moreover, just when Europeans started their impassioned debates over these new observations and put forth their alternative ideas, the Ottoman, Mughal, and Chinese Empires were focused on internal concerns, seeking to recover from internal rebellions by closing off outside influences and strengthening traditional orthodox beliefs.

Thus the Europeans, more than any other major civilization, suddenly found that the classical tradition that they had sought to embrace now had to be escaped if they were going to understand the true nature of their world and their universe. This led Europeans to undertake a search for new systems of philosophy and new ways of studying and describing nature.

Searching for New Directions in European Science: Cartesian Reasoning and British Empiricism, 1650–1750

Prior to 1650, all major civilizations drew on four basic sources to justify knowledge and authority (which were generally closely connected). These were

1. Tradition—knowledge that was revered for its age and long use
2. Religion or revelation—knowledge that was based on sacred texts or the sayings of prophets, saints, and other spiritual leaders
3. Reason—knowledge that was obtained from logical demonstration, either in arithmetic and geometry or by deductive reasoning from basic premises

4. Repeated observation and experience—knowledge that was confirmed by widely shared and repeated observations and everyday experience, such as that day follows night, the sun rises in the east, objects fall, heat rises. This also includes various agricultural and manufacturing techniques that were proven in use.

We have noted that in Europe by the early 1600s new discoveries, observations, and concepts about the Earth and the universe had already started to chip away at tradition and religious belief as guides to knowledge about the natural world. In addition, the seventeenth century was a period of sharp religious schism and conflict in Europe, capped by the Thirty Years' War (1618–1648). During these years Catholics, Lutherans, Calvinists, and other sects all claimed to be correcting the errors of others' interpretation of Christian faith, and various religious groups rebelled and embroiled Europe in massive civil and international wars. The lack of accepted religious authority and of any way to choose between competing claims seemed to offer nothing but the prospect of endless conflict.

The same problems, as we have noted, led Asian empires to promote a return to their traditional orthodox beliefs to suppress these conflicts. Some European states tried to do the same thing. In Spain and Italy and part of Germany and Poland, the counter-Reformation led to the suppression of heresies and unorthodox views and enforcement of traditional Catholic beliefs. These states banned books that threatened Catholic orthodoxy and sought to curtail the actions of "dangerous" authors, such as Giordano Bruno and Galileo (Bruno was burned at the stake for his heresies; Galileo, more prudent and better connected, was allowed to live under house arrest). France and the Netherlands, though less severe, and Britain through 1640, also tried to restore uniform state religions and force dissenters underground or into exile. However, in a few states—including Britain after 1689, Denmark, and Prussia—religious tolerance remained, and throughout western Europe, there was a checkerboard of different states following different varieties of religion—Catholic, Calvinist, Lutheran. Throughout Europe, the result of the rise and spread of Protestantism in the sixteenth and seventeenth centuries was that the authority of the Catholic Church—and of the philosophical and scientific work that was closely associated with the church's teachings—was seriously weakened. This provided an additional reason for philosophers to struggle to find a new basis for more certain knowledge.

European thinkers therefore turned away from the first and second major sources of knowledge and authority—tradition and religion—to seek new systems of knowledge. After 1650, two major directions were proposed to deal with this dilemma—rationalism and empiricism.

One way to set aside traditional and revelation-based assump was to try to get down to bedrock conclusions by reasoning purely fro logic. The critical figure leading this approach was the French philo pher and mathematician René Descartes, who resolved to begin by dou ing everything—the teaching of the ancients, the teachings of the chur and even his own experience. He extended his doubt until only one th remained certain—the fact of his own doubt! This fact could then be th basis for logical deductions. After all, if Descartes could not escape th fact of his own doubt, he—as a doubting, thinking entity—must ex This conclusion was rendered in his famous statement "I think, therefo I am."

Descartes continued this argument further. If he doubted, he cou not be perfect. But if he was aware of his imperfection, this could on be because a perfect entity existed, thus there must be a perfect being, o God. And because we can only conceive of God as perfect, and hen perfectly logical, the universe constructed by God must also follow pe fect logic. Descartes further argued that we can only logically perce space if something is there, extending through space (empty space, Des cartes argued, was a logical contradiction). What must fill space, the are invisible particles whose motions and interactions must cause all th we see.

In this fashion, Descartes built up a logically consistent model of mechanical universe in which all phenomena are to be explained by th movements and collisions of moving particles. This led Descartes to numerous valuable insights, such as the notion that we see things be cause invisible particles of light move from the objects we see to stri our eyes. But it also led him to deduce things that we now know a simply not true, such as the idea that the planets travel around the Su because they are caught up in vortexes or whirlpools of swirling invi ible particles.

This Cartesian rationalism provided a very attractive alternative t Aristotelian philosophy, which was now in disrepute. It seemed to hav the power of purely logical demonstration behind its ideas. Also, becau all phenomena were reduced to the motions of particles, it held th promise of applying mathematical principles—already worked out b Galileo for many kinds of particle motion—to all of nature. Finally, i allowed one to explain almost anything by coming up with some char acteristics of particles. For example, one could suggest that spicy o sweet flavors were the respective results of sharp or smooth particles hi ting the tongue or that different colors of light were produced by pa ticles of light spinning at different speeds.

However, Cartesian rationalism also had its defects. In putting re son above experience, Cartesians disdained experiments. This limit what could be learned or discovered and often led to significant erro Descartes' assumptions led him to misjudge the way bodies acted collisions and turned his followers away from studying the properties of vacuums (since empty space could not exist, they must be tricks or errors by experimenters). Descartes also flatly ruled out the possibility of forces acting directly across space between objects, such as gravity. For all of its virtues, Cartesian rationalism therefore saddled its followers with a variety of errors and false explanations of the mechanics of motion in nature.

The motion of the Earth, the weight of the atmosphere, and the properties of vacuums were all discoveries whose proof rested on the use of scientific instruments (telescopes, barometers, vacuum pumps) to capture information not ordinarily available to the senses. The use of such instruments was a prime feature of the Baconian plan of developing scientific knowledge by experiments.

The experimental program reached its most systematic organization in the work of the Royal Society of London, led by Robert Boyle and later by Isaac Newton. The Royal Society based its research on experiments with scientific instruments and apparatus publicly performed at meetings of the society, and accounts of those experiments were widely published. The Royal Society used air pumps, telescopes, microscopes, electrostatic generators, prisms, lenses, and a variety of other tools to carry out its investigations. Indeed, the society came to rely on specially trained craftspeople to supply the growing demand for scientific instruments for its members.

The fame of the Royal Society in Britain skyrocketed with the achievements of Isaac Newton. Newton was the first to demonstrate that both motion on the Earth—whether the movement of falling apples, cannonballs, or the tides—and the motions of the planets through the heavens could *all* be explained by the action of a universal force of gravity. This force acted to attract objects to each other with a strength that increased with their mass but decreased with the inverse square of the distance between them. Newton's theory of gravity made it possible, for the first time, to explain the precise path and speed that the planets followed through the skies, as well as the movement of the Moon and the tides.

Newton also discovered the correct laws of mechanical force—that force was needed for all changes in the direction or speed of motion of an object, in proportion to the mass of the object and the magnitude of the change. Newton's laws of force made it possible to easily figure out the amount of work provided by, for example, a volume of falling water based on the height that it fell, or the amount of work it would take to raise a certain weight a desired distance. Newton further discovered the key principle of optics: that white light was composed of a number of different colors of light, each of which bent slightly differently when passing through water or a glass lens, thus creating rainbows in the sky and color patterns in prisms and lenses. . . .