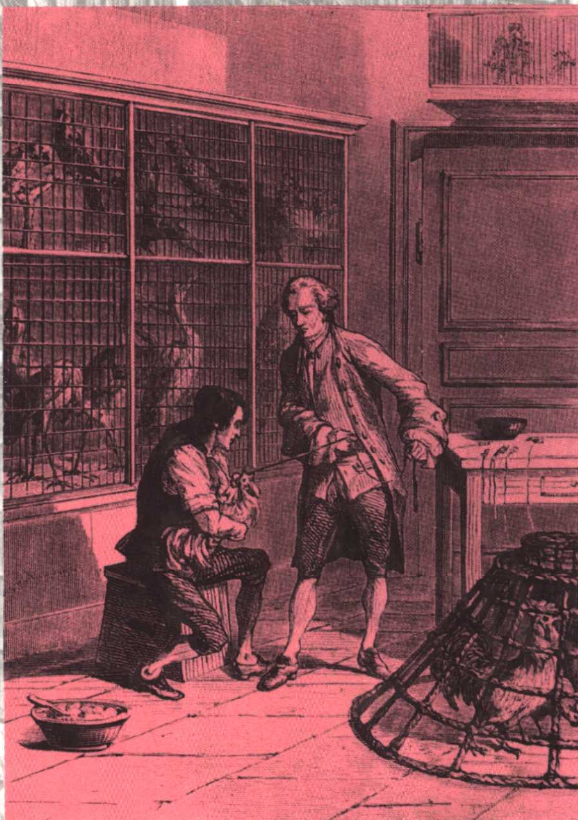
ON THE SHOULDERS OF GIANTS

THE HISTORY OF SCIENCE



IN THE EIGHTEENTH CENTURY

Ray Spangenburg and Diane K. Moser

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Facts On File

On the cover: Lazzaro Spallanzani performs an experiment on digestion in birds. (Figuier, *Vie des Savants*, 1870 [Courtesy, North Dakota State University Library])

The History of Science in the Eighteenth Century

Facts On File, Inc.
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P R O L O G U E

THE STORY SO FAR: THE COPERNICAN SYSTEM AND THE SCIENTIFIC REVOLUTION

People have always looked for knowledge in various ways, delving for explanations and searching their world for answers. And people have always used the richness of their minds—their imaginations and their faith—to bridge what seemed impossible to understand. From the beginning of time they have told stories of gods and superhuman men and women who forged the forces that made the world work, the Sun rise, the rains come and the harvests grow. And shamans and priests fashioned rituals by which they sought to control pestilence and disease and to drive away drought.

However, from earliest times human beings have also used their powers of observation and calculation. Very early, people in several areas of the world—including China and the Mesopotamian basin—began to develop the tools of mathematics, language and writing. And they developed more quantitative and objective approaches to explaining. By 1800 B.C., the Sumerians in the Middle East and the Babylonians, who succeeded them, had made many accurate observations about the stars and planets and had developed numerical systems and ways to keep records. Cuneiform and pictograph writing systems began even earlier and by 1300 B.C., the Phoenicians had alphabets based on earlier systems developed by the Egyptians and the Babylonians. And by the time of the ancient Greeks, in the last four or five centuries B.C., analytical methods, logic and geometry began to be finely honed. Several Greek thinkers, especially, began to explore more nonmystical explanations. And Aristotle (384–322 B.C.), perhaps the greatest Greek thinker, and several of his followers, including a man named Ptolemy, also devised the first integrated natural theory about how the universe worked, with intricate visions of nested spheres that held the planets and the stars and circled around the Earth.

Greek ideas about mathematics, philosophy and science reigned supreme up to the fall of the Roman Empire, when many manuscripts were burned as cities were sacked by barbarian invasions. But some were preserved, largely by Islamic priests, and later passed into hands of monks in the monasteries of Europe. Partly as a result of this preservation, and partly because no one questioned it, Aristotle and Ptolemy's concept of a universe composed of concentric spheres revolving around the Earth remained the best explanation of the cosmos anyone came up with for some 14 centuries.

Then, in a daring sweep of imagination, the Polish theorist Nicolaus Copernicus revised that theory in the 16th century by placing the Sun, not the Earth, at the center of the circling planets. Called the Copernican system, this Sun-centered view of the Solar System (and actually, the universe, at the time) turned every doctrine and assumption about the world and humanity's place in it upside-down. When two more great astronomers, the Danish observer Tycho Brahe (1546–1601) and his one-time assistant from Germany, Johannes Kepler (1571–1630), added their own observations and calculations to verify Copernicus's ideas, most people thought they, too, were heretics. And when the Italian astronomer Galileo Galilei (1564–1642) defended the idea in his book *Dialogue on the Two Chief Systems of the World*, published in 1632, he was tried by the Catholic church and his book was banned—put on the Index, where it stayed until 1835. (Not until 1992, in fact, did the pope declare that Galileo was not in error.) Even though careful inquiry and reasoning supported Copernicus's idea, a Sun-centered solar system didn't make sense if one took certain passages of the Bible literally. Theologians and their followers pointed significantly to the Old Testament story in which God stopped the movement of the Sun across the sky so that the people led by Joshua could win a crucial battle. The Sun, then, must be moving around the Earth and not vice versa. To resolve the conflict between nature observed and the Bible's authority, church authorities recommended keeping faith with the Bible. Church doctrine also maintained that humanity was created in God's image and that therefore God would not have created the universe in a way that did not revolve around the Earth. And so a battle raged between those who wanted to rely on human ability to find things out through the use of the mind and the senses and those who preferred to depend on traditional authority for answers.

Nearly everyone today takes Copernicus's idea for granted that the Earth revolves around the Sun. But the stir his ideas caused in his time, and Galileo's, is a reminder of how hard it is to let go of old ways of thinking in the light of new facts. What made arguments for the Copernican system so powerful at the time, even against the spiritual and political strength of religion and tradition, was the birth of a new methodology, spawned in large part by the experimental work of Galileo, an extraordinarily effective approach to problem solving that came to be known as the scientific method (explained in more detail in the Appendix). Scientific method calls for explanations based on observation, on collected facts and measurements—not on reasoning alone or on emotional reactions, visions, hearsay or faith. And the scientific method accepts only explanations that can be verified over and over by experiments. The results of these experiments, summarized in theories, can then be used to make predictions about other phenomena not yet observed. Then when the opportunity arises to test one of these predictions, the results of that test can be compared to the predicted results. In this way, the results of experiments and observations are constantly used to modify existing theories—which is what makes science a "self-correcting" process. This fundamental change in the way people looked at the world, which took place in the period just preceding the first years covered in this book, is commonly referred to as the scientific revolution.

Many of the most important scientific discoveries in the 17th century had centered in Italy. Even the Polish astronomer Copernicus had trained there in the 1490s, and while Tycho and Kepler had come from the more northern regions of Denmark and Germany, the great names in the life sciences either trained in Italy or were born there. Among many others, Andreas Vesalius (1514–64), the Flemish father of human anatomy, William Harvey (1578–1657), the English physician who made breakthrough progress in the area of blood circulation, and Marcello Malpighi (1628–94), the Italian physiologist who discovered capillaries in frogs' lungs, studied in Italy.

But by the end of the century the focus of growth had begun to shift north to France and England. In England, especially, economic dependence on far-flung colonies in North America, Africa and Asia created an urgent need for reliable knowledge about navigation. The English government—understanding that knowledge of the stars and their positions was the key to navigation—created the position of Royal Astronomer and John Flamsteed (1646–1719) was appointed to the post. Edmund Halley (1656–1742), Christopher Wren (1632–1723) and Robert Hooke (1635–1703), among others, formed a society of scientists called the Royal Society in 1662. (Its motto, Nullius in Verba—take nobody's word; see for yourself—set the stage for the century to come.) The greatest of all English scientists, Isaac Newton, became a member of the Society in 1671, and in 1687 he published a book called *Principia mathematica* that synthesized the ideas of the scientific revolution and set forth basic principles of the universe, "laws" of motion that nature followed, in a more cohesive way than anyone ever had before.

In what are now known as Newton's three laws of motion, the great English synthesizer mathematically demonstrated principles that Galileo explored with some of his experiments:

1. the principle of inertia (a body at rest remains at rest and a body in motion remains in motion at a constant velocity as long as outside forces are not involved);
2. definition of a force in terms of mass and acceleration; and
3. the famous statement that for every action there is an equal and opposite reaction (the principle that governs the behavior of rockets).

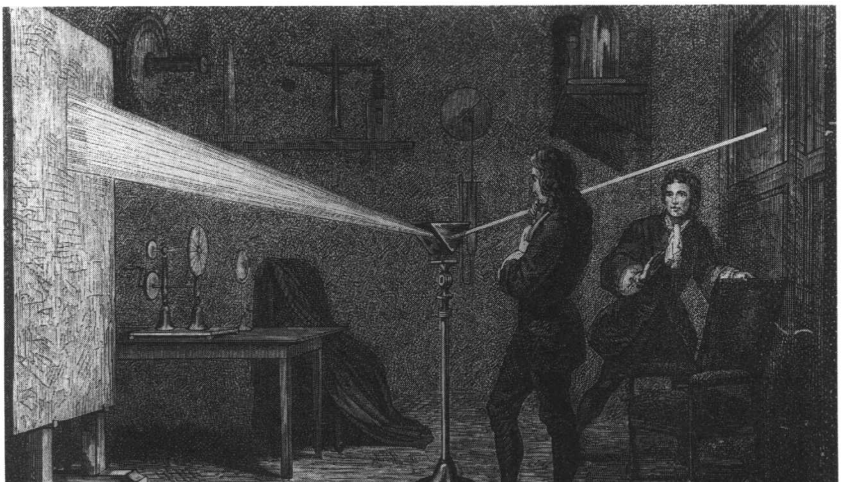
By the beginning of the 18th century, the scientific revolution, based on the work of such intellectual giants as Galileo and Newton, had established a new way of perceiving nature and had forever altered humanity's understanding of itself and the universe.

The History of Science in the Eighteenth Century is one of a series of five books, called On the Shoulders of Giants, which looks at how people have developed the methods of science as a system for finding out how the world works. We will look at the theories they put forth, sometimes right and sometimes wrong. And we will look at how we have learned to test, accept and build upon those theories—or to correct, expand or simplify them.

We'll also see how scientists have learned from others' mistakes, sometimes having to discard theories that once seemed logical but later proved to be incorrect, misleading or unfruitful. In all these ways these men and women—and the rest of us as well—have built upon the shoulders of the men and women of science, the giants, who went before them.

THE EIGHTEENTH CENTURY— A TIME OF REASON AND REVOLUTION

Variously called the Enlightenment or the Age of Reason, and even, sometimes, the Age of Confidence, the 18th century was a time of enormous optimism about the power of human reason to discover all ultimate truths and overcome all problems, intellectual, philosophical and social. From the great thinkers of the scientific revolution—Nicolaus Copernicus, Galileo Galilei and Isaac Newton—they had inherited a key that seemed capable of unlocking all the secrets of Nature. And at the dawn of



Newton in his laboratory studying the nature of light (Louis Figuier: *Vies des savants illustres depuis l'antiquité jusqu'au dix-neuvième siècle*, vol. V: *Savants du XVIIIe siècle*, 1870) the 18th century the world—in fact, the entire universe—began to seem altogether knowable.

Of course, the farmer tilling his fields, the midwife calmly performing her duties and the shopkeeper selling his wares had little time left in their crowded days to contemplate the nature of the universe or humankind's place in it. But even the farmer, the midwife and the merchant, along with millions of others, found that the spirit of the times was changing. Not everyone liked the transformation, and not everyone understood it or accepted it, but by the end of the century it had touched the lives of virtually everyone in the Western world. The 18th century's three great revolutions—the American, the French and the Industrial—were all touched off by this new outlook, and its impact helped to define the world we live in today.

At the heart of this change stood Newton, his *Principia mathematica* and the natural laws of gravity and motion he uncovered. Nature, Newton had demonstrated, played by rules. And the rules appeared to be regular and identifiable. Nature was no longer seen as a capricious and unpredictable force; instead it was governed by basic laws that it always obeyed. For the thinkers of the 18th century Newton's discovery of the existence of these laws disclosed a clockwork universe. They saw the world as a machine. And they thought that one could understand the world-machine in the same way that a skilled craftsperson who had never seen the inside of a clock might take one apart, examine its parts and their relationships, apply common sense and reason and comprehend how it worked.

Newton, building on the work of Copernicus, Tycho Brahe, Kepler and Galileo before him, gave final proof to the power of the scientific method. And this new approach to nature had caused an avalanche of consequences in his time. Not only did 17th-century scientists set straight many ancient distortions about the way the physical world worked, but some—most notably the English physiologist William Harvey—also used the new method to discover the internal mechanisms of the human body. And, while progress in biology occasionally stumbled when scientists applied too strict a "Newtonian" and "mechanistic" interpretation to human physiology, 18th-century thinkers saw that it was possible to use the scientific method of observation and experimentation to answer many difficult questions successfully. No longer would answers have to come from the books and writings of ancient thinkers or the unchallengeable word of religious authorities.

This new outlook liberated the thinkers of the 18th century from the authority of ancient Greek theories that had never been tested by experiment or observation. Knowledge of the world, they realized, could be acquired, not passively from Greek and Latin manuscripts and wizened scholars, but from the active, curious and disciplined engagement of their minds applying rational thinking, combined with experimentation and observation, to a variety of problems.

Was there room in this new "enlightened" view for religion? Newton himself was troubled by this question. Devoutly religious, Newton never gave up his belief in God. He believed in fact that it was occasionally necessary for God to intervene to keep the Solar System working in its beautiful machinelike precision. Finally he concluded that the wonderful machinery of the universe, in all its clockwork precision, demonstrated the magnificent power and majesty of its creator. In the 18th century, after it was discovered by mathematical analysis that God's intervention was not necessary to keep the Solar System stable, many adopted a religious view called deism. This view held that God had created the world and all of its natural laws but, having finished the job, had left the machinery to run by itself. As Newton had foreseen, though, this view left some people wondering whether a clockwork universe required the existence of God at all. Consequently—and this possibility had troubled Newton—some of the enlightenment thinkers became atheists, denying the need or existence of any god. One group especially, the philosophes in France, strove to build a moral philosophy based not on revealed religion, but on human ethical thought. Their ranks included such great thinkers as Voltaire, Diderot and Montesquieu. So, while by far the vast majority remained theists, maintaining their allegiance to God and the traditional teachings of religion about miracles, Newton's legacy also introduced new doubts about fundamental issues of religion and philosophy.

It presented new questions about social structure and values as well. Scientists had discovered that nature had "natural laws." Was it possible that similar natural "laws" might govern all moral, social and political activities? If that was the case, many believed, then by applying rational thinking, those laws could also be discovered and turned toward the benefit of humanity. Philosophers such as Immanuel Kant (who coined the term *enlightenment* to describe the new dawn of reason and the intellectual brilliance of the time), David Hume, Gottfried Wilhelm Leibniz, François Marie Arouet (known as Voltaire), Jean-Jacques Rousseau and others sought to find a place for humanity in the new perspective brought by science to the world. Some, like Voltaire, who attended Newton's funeral, became vocal and dynamic champions of the new scientific-sociopolitical views. Writers such as the French journalist Denis Diderot, who supervised the first 28 volumes of the great *Encyclopédie*, brought the new ideas of science and philosophy to the general public.

In Paris, writers, philosophers and artists gathered at *salons* in the homes of wealthy and intelligent French women, who invited them to meet there and exchange views. It was a time when lively, impassioned and closely reasoned discussion flew among the philosophes, not only at the salons of

Paris, but also in lengthy correspondence in which a number of women also took part. Few women were permitted the education needed to contribute in more direct ways, but a notable exception in these circles was Emilie du Châtelet, whose translation of the work of Newton from Latin to French was responsible for its wide dissemination and much of its influence in France. Several women took an active part in the advances of science, as will be pointed out in the chapters of this book.

The new thinking of the Enlightenment burst like fireworks across the social, geographical and political boundaries of the Western world. Across the Atlantic in the American colonies it kindled the thinking of political leaders and molders of government such as Thomas Jefferson, Thomas Paine and scientist-statesmen-author Benjamin Franklin. Jefferson, as well as many other intelligent and well-read people of the 18th century, particularly felt the influence of the English philosopher John Locke (1632–1704). In his work *An Essay Concerning Human Understanding*, published in 1690, Locke declared that there were natural laws constructed by God to ensure the happiness and welfare of humanity. Paramount among those laws were the rights of life, liberty and property. Furthermore, Locke argued, while people originally lived in a state of nature free from restriction or restraint, the strong had violated that peaceful existence and taken unfair advantage over the weak. To defend themselves from such cruelty and enjoy their God-given rights people had chosen rulers under special agreements. In exchange for the ruler's protection and aid in holding onto their natural rights, they had agreed to abide by the ruler's decisions and dictates. If a ruler began to violate those natural rights, though, argued Locke, then the people had the right to disobey and, if necessary, to overthrow that ruler.

In England, the idea of natural human rights had already grown strong during the 17th century, as Parliament struggled to wrest power away from an autocratic monarchy. In 1628 Parliament forced King Charles I to sign the Petition of Right, which required approval of taxes by Parliament, established limitations on military law and held that no person could be imprisoned without a specific charge. In a civil war beginning in 1642, following several despotic moves by Charles, Parliament overthrew the king, replacing the monarchy with a republic headed by a Puritan general named Oliver Cromwell. But the revolution faltered at Cromwell's death in 1658, and in 1660 Parliament invited Charles II, son of the executed king, to take the throne. But Parliament took control again in 1688. In a move known as the Glorious Revolution, they offered the crown to the king's Protestant daughter Mary and her husband, William of Orange, over her Catholic brother James, who was next in line. And in 1689, the year before Locke published his *Essay*, Parliament drew up what is known as the English Bill of Rights. These events in England, combined with the influence of the scientific revolution, had great effect on government in the Western world.

In Britain they established parliamentary government, rule by law, limited monarchy and the protection of individual liberties.

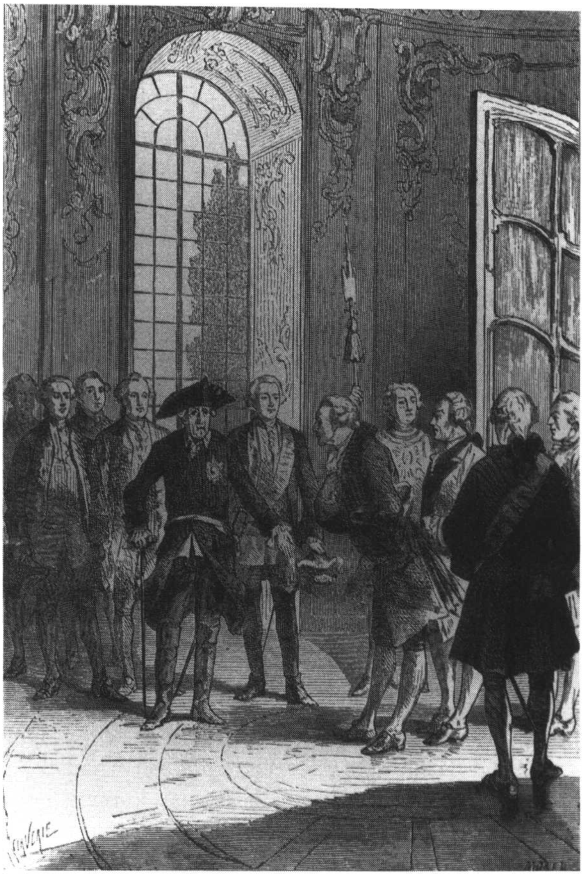
Many French thinkers in the 18th century admired the English government and strove to develop philosophies of human government, education and society that reflected reasoned and just policies, based on an understanding of the essence of what it means to be human. These philosophes also left a powerful mark on the intellectual climate of the time. They promoted reform in France, reacting against the excesses of the absolute monarchy that ruled there. They objected to preferences given to nobility, who paid few taxes and received the best positions by right of birth. And the philosophes rankled against the special rights accorded the Catholic church in France, which paid no taxes and had the right to censor books, restricting their publication (as it did Galileo's *Dialogue on the Two Chief Systems of the World*).

Some, like the baron de Montesquieu, although himself a privileged aristocrat, focused on formulating governmental policies that would ensure individual rights for all. He suggested the principle of separation of powers, dividing authority among three branches of government, a system that greatly influenced the authors of the U.S. Constitution. He maintained that, by separating the legislative, executive and judicial powers, no one entity would ever have absolute authority.

The spirit of the time was so rich with ideas and new achievements that many of the philosophes, spearheaded by Denis Diderot and Jean d'Alembert, set out to collect and publish exhaustive information on science, technology and other fields of human knowledge. They called their work the *Encyclopédie*, and many of their contemporaries contributed articles, including Voltaire, Montesquieu and others. The first volumes appeared in 1751, but both the French government and church censors immediately banned it for encouraging a spirit of revolt, as well as promoting "moral corruption, . . . irreligion, and . . . unbelief." Diderot finally convinced the censors to release some of the volumes, but many of the articles had to be carefully worded to avoid arousing their anger again. Publication continued until 1772, and more than two dozen volumes finally appeared.

The philosophes supported Locke's view that people were born neither good nor evil, and that a child's mind was like a blank tablet on which no one has written. Nine out of 10 people, wrote Locke, "are good or evil, useful or not, [as a result of] their education." The idea had profound political implications—that people should have no special treatment by right of birth, only on the basis of their ability to contribute, which depended on their education. Society could produce good citizens through good education.

Across the ocean, Jefferson and his colleagues would borrow many of Locke's ideas when the American colonies sought to free themselves from the



Frederick II of Prussia considered himself a great friend of science. Here he welcomes the philosophe and encyclopedist Jean d'Alembert to Berlin. (Figuier: *Vies des savants*, 1870)

economic and political encumbrance of British rule. The American Declaration of Independence, which echoed many of Locke's ideas, the American Revolution of 1776, the American Bill of Rights and the democratic government that replaced the colonial regime all reflect Locke's influence.

In Europe, many 18th-century monarchs such as Prussia's Frederick II (1744-97) saw themselves as "enlightened rulers." Often though, while intellectually paying lip service to the new ideas on human rights sweeping around them, these rulers still held a tight grip on the lives of the people they saw as their subjects, showing attitudes held over from the medieval days of serfdom, when kings felt they owned their subjects and all they produced.

In France, the home of some of the greatest Enlightenment thinkers and scientists, change came later, and when it came it was violent, confused and bloody. Change was long overdue, and the French were not content to watch the English and the Americans enjoy the recognition of human rights while their society still labored under an outdated feudal system, plagued with economic inequality, special class privileges and the absolute rule of kings. At the same time that the philosophes were writing about equal rights, the French bourgeoisie, or middle class, was growing stronger, more well-to-do and more ambitious; the peasants and city workers lived in poverty; and the nobles sought even more power. France, meanwhile, faced a grave economic crisis. King Louis XIV, who died in 1715, had spent lavishly on luxurious living and wars. In his wake he left enormous debts. Those who followed, Louis XV and Louis XVI, borrowed more and spent even more lavishly. Because the church and the nobility were largely protected from taxation, and even most of the wealthy bourgeoisie were exempt, the only sources of revenue were the poverty-stricken peasants and city workers. In June 1789, the bourgeoisie tried to change the order of government by establishing a new legislative body called the National Assembly. But revolt was inevitable. On July 14, 1789, Parisians massed outside the Bastille, the great fortress prison that symbolized the monarchy's injustices and oppression. The angry mob stormed the prison, killing the commander and some of the guards; the Revolution had begun and the bloodshed did not stop for years. Louis XVI was sent to the guillotine in January 1793. His wife, Marie Antoinette, was executed the same year. A period known as the Reign of Terror began and between September 1793 and July 1794 at least 20,000 people (possibly even twice that many) were executed. But when the bloodshed ended at last and a new constitution was adopted in 1795, in France, too, the new constitutional government established many of the Enlightenment principles of the philosophes—including guarantees of individual rights. When Napoléon Bonaparte came to power in 1799 as first consul, he established a new system of laws, the Code Napoléon, based on the ideals of the Revolution.

Meanwhile, another kind of transformation—the mechanization of production known as the Industrial Revolution—began to change the shape of the economic world. The Industrial Revolution began about 1750–60, primarily in Great Britain, where a combination of factors, including advances in agriculture, converged to make dramatic changes possible—changes that had both positive and negative effects. In 1701 a man named Jethro Tull invented a mechanical seeder. A horse-drawn hoe soon followed, and, as a result, food production increased so dramatically that Great Britain could now feed its growing population without importing as much food as before, thus freeing up financial resources to import raw materials for other kinds of production. In its colonies, Britain had good sources of supply, especially for cotton, and good markets for manufactured products.

The textile industry, which relied at the time on hundreds of weavers and spinners isolated in their cottages, was the first to be dramatically

JOHN KAY AND THE FLYING SHUTTLE

One of the most influential of the earliest inventions of the Industrial Revolution was John Kay's flying shuttle. Patented in 1733, the machine was an improvement on the weaver's loom. Before Kay's invention, two weavers were needed to weave a wide piece of cloth. Each would stand on opposite sides of the loom and toss the shuttle back and forth across the width of the cloth. Kay's invention was simple. He mounted his shuttle on small rollers so that it would roll back and forth on a wooden rail. One weaver then could quickly move it from side to side by pulling on a chord that caused wooden hammers to hit it back and forth.

While the invention increased the speed of the weaving and made it possible to weave wider cloth than had been woven before, it also eliminated one of the two weavers previously needed for the job. That was not a happy situation for the weavers of Colchester where Kay first introduced his invention. They argued that Kay was trying to take their jobs away from them. Kay argued that more weavers would be needed to produce even more cloth than had been produced before, but that did not settle the problem of the weavers, who were afraid that until the demand for cloth increased, they would still be out of work.

Kay took his machine to Leeds, hoping to drum up some interest there, but his luck took another bad turn. The manufacturers at Leeds liked the machine but refused to pay him royalties for its use. His lawsuits against them proved practically useless when they united and fought him in the courts, costing him most of his money in heavy court expenses.

Disheartened and nearly broke, Kay returned to his native town of Bury, England in 1745. The flying shuttle had caught on and begun to replace weavers across England. Even though he was not making money with his invention, groups of angry laborers rioted and broke into his house, looting it and forcing him to flee. He escaped to Manchester, but eventually he was also forced to flee that city, hiding in a sack of wool. Feeling unsafe in England, Kay emigrated to France, where he died penniless.

transformed by a series of inventions. In 1733 John Kay invented the flying shuttle to speed weaving—with the result that one weaver could use all the thread produced by several spinners. In the 1760s James Hargreaves invented what he called a spinning jenny, a device that enabled a spinner to turn a series of spindles by using a single spinning wheel. The power that ran both these "machines" was still human power, but by 1769, Richard Arkwright had figured out how to use water power to run a spinning machine, and by 1785, Edmund Cartwright had invented a loom run by water power. Now the weak point in production was obtaining enough raw materials to supply the speeding spinners and weavers, especially cotton fiber, which holds its seeds tangled tightly among its strands. But in 1793, an American inventor, Eli Whitney, solved that problem with the invention of his cotton gin, which stripped the seeds out automatically.

By now the new machines began to be too expensive for individual weavers to rent or own, and with the new use of water power, it became necessary to have a source of running water nearby for weaving and spinning. And so, entrepreneurs began to build and organize factories for efficient production, purchasing the equipment, hiring workers and locating new markets for the goods. Textile manufacturers began to replace the cottage industry they had always relied on with a vastly more efficient factory system. The result was more goods produced more quickly—and they were cheaper and more readily available, an advance that everyone profited from.

Advances in iron production and Eli Whitney's concept of standard interchangeable parts for manufacturing machinery made the development of machinery more efficient, too. And in 1769 James Watt developed the first practical steam engine. Now, because England had excellent coal and iron ore resources, a cheap source of power was available to streamline almost every industry.

The social effects, however, were not all positive. Factory owners expected long hours of intensive, repetitive work. Working conditions were unpleasant and unsafe, and children, who had always worked alongside their parents in the cottage industries, were employed by the factories and exposed to many hazardous conditions. Workers no longer enjoyed the freedom and independence of working at home, and they spent large portions of every day in unpleasant surroundings, under the watchful eye of a factory boss. Reforms were long in coming and much of the bucolic life of the British countryside was transformed into a series of sprawling, increasingly noisy and dirty industrial towns and cities. But reforms did come eventually, people learned how to use the new technologies more humanely and the Industrial Revolution produced enormous improvements to the general standard of living. In addition, the technologies that it put in motion set the stage for many more advances—including electricity—that would arrive in the following century.

For many historians the period of the Enlightenment ended between 1776 (at the time of the American Declaration of Independence) and 1789 (with the fall of the Bastille and the beginning of the French Revolution). Already, though, before these dramatic events, a reaction had begun slowly to erode the reign of Enlightenment ideals of rational and scientific philosophy. Not everyone had embraced the doctrine of reason. Some thinkers, among them Jean-Jacques Rousseau, detested and feared both