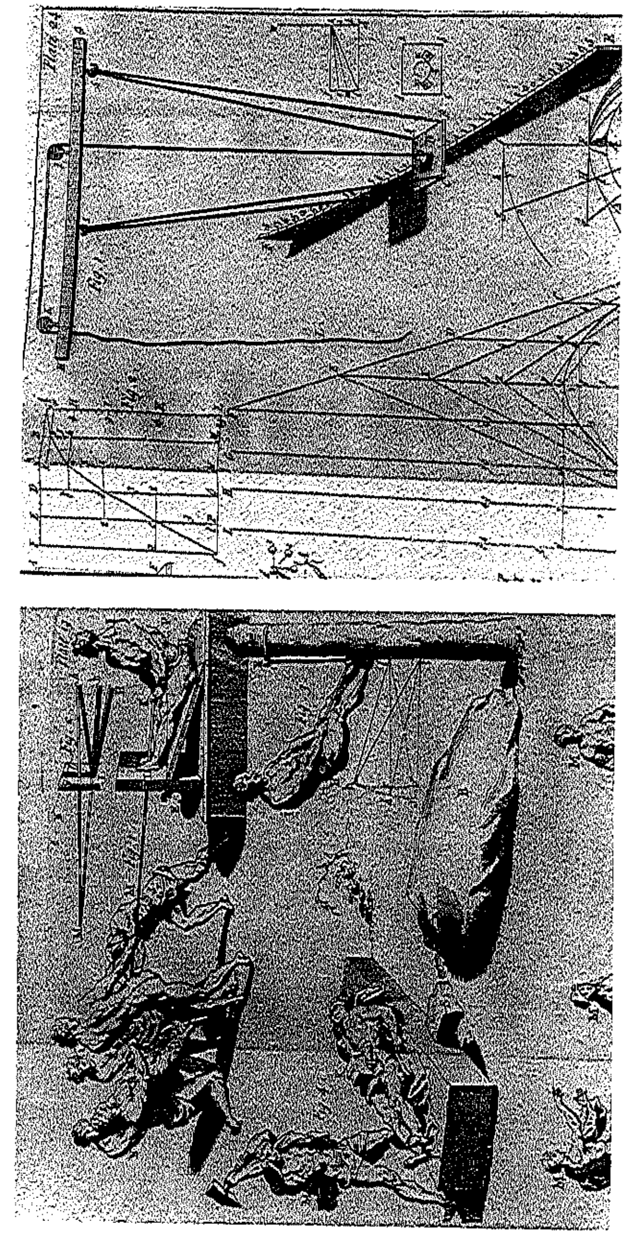
out of which he extracted principles useful to manufacturing. The 1717 edition of Newton's *Opticks* spoke about the elasticity of fluids. Desaguliers applied the concept to steam, arguing that it maintained its heat and elasticity and could therefore be contained in copper vessels in close contact with other volatile substances in need of heat but too dangerous to place near fire. Through the transfer of steam heat from vessel to vessel even gunpowder could be dried safely. [77] In cooperation with a coppersmith and an instrument maker, Desaguliers presented his device to the Royal Society, and in 1730 he secured a patent for it. Desaguliers did not die a rich man, but it was not from want of trying. In many aspects of his career Desaguliers was more entrepreneur than clergyman, more engineer than simple experimenter.

The Spread of Newtonianism

In lectures given throughout Britain and in the Low Countries (where he spoke in French or Latin), Desaguliers offered something for almost any skilled craftsman, merchant, or self-improving listener. The published version of his lectures, complete with careful and exquisite drawings, could be used for the education of other Newtonian practitioners or for self-education by entrepreneurs whose success depended upon the skill of the engineers whom they hired. A course of a dozen lectures cost about two guineas, the price of dancing instructions with a good master. By virtue of his breadth and clarity, Desaguliers became the most famous of literally hundreds of eighteenth-century Newtonian practitioners who applied the mechanical legacy of the *Principia* to a wide range of practical problems, from the draining of mines and swamps to the building of canals and electrical experimentation.

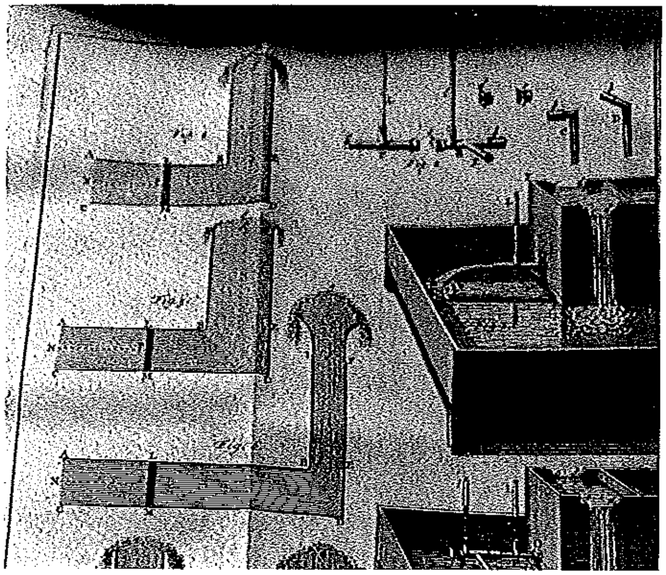
Courses in all these topics became institutionalized particularly in the academies run by the non-Anglican Dissenters. As late as the 1820s the natural philosophy curriculum found in them closely followed the topics set forth in Desaguliers's two-volume *Course* published in the 1740s.[9] As we shall see shortly, such courses cannot be separated from the cultural history of early industrialization in Britain. Even more so than Cambridge, the Dissenting academies, whether in London or Manchester, led the field in science education, and by the late eighteenth century any self-respecting business family with industrial interests opted first to send their adolescent boys to such an academy, or possibly to Edinburgh University, where medical and scientific education was among the best to be found in Europe. In these schools of higher education students used mechanical instruments and devices.



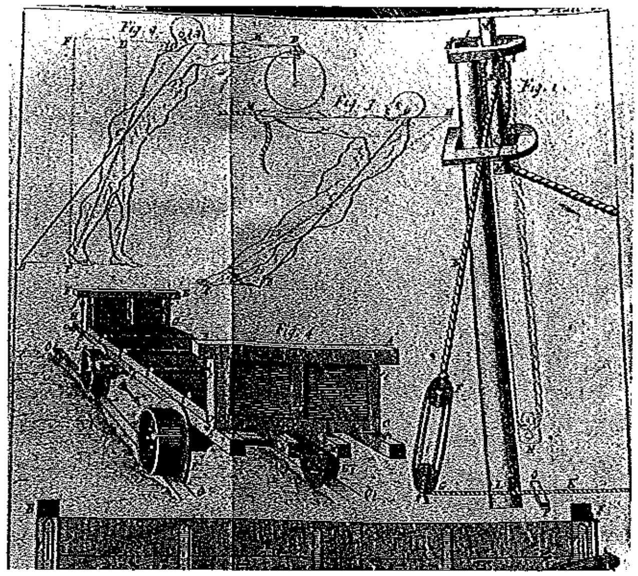
b

a

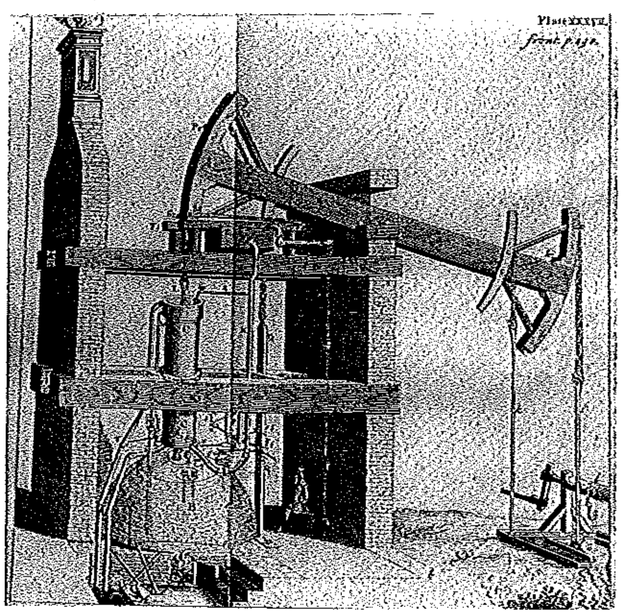
FIGURE 2.4 All illustrations taken from Desaguliers's *Course of Experimental Philosophy*, these pictures first explained how human strength must struggle against gravity and inertia (2.4a), then illustrated how these forces can be measured (2.4b), went on in subsequent lectures to discuss the movement of water (2.4c) and the removal of coal from mines (2.4d), and ended with contemporary steam engines and water wheels (2.4e, f). Courtesy of Van Pelt Library, University of Pennsylvania.



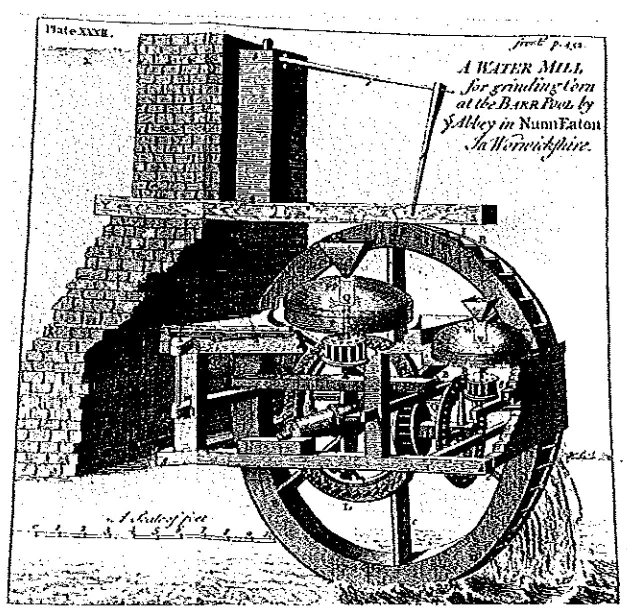
c



d



e


A WATER MILL
for grinding Corn
at the BARR POOL by
ye Abbey in Nunn Eaton
in Warwickshire.

f

They learned hands-on mechanics, hydrostatics, pneumatics, or optics, or they could begin medical education that had been shaped by experimental approaches indebted to Newtonian science.

Part of Desaguliers's success as a lecturer, and indeed the efficacy of Newtonian demonstration in general, depended upon the quality of instrumentation available in London, the English provinces, and then slowly in the American colonies. In the seventeenth century the Dutch had been the greatest instrument makers, but gradually the art shifted across the English Channel. To this day eighteenth-century instruments can be seen in museums or in the collections of older British and American universities from Oxford to Harvard, Yale, Columbia, Princeton, and William and Mary in Virginia. [37] At the College of Philadelphia, later the University of Pennsylvania, students were required to spend 40 percent of their time on scientific subjects. Air pumps, telescopes, globes, thermometers, orreries—all were part of standard classroom experience. [3] Orreries re-created the Newtonian universe, complete with moving parts that could illustrate the positions of the planets by the turn of a handle that set this miniature universe into harmonious motion. For the wealthy, orreries, exquisitely crafted in brass and wood, could be purchased as objets d'art, thus bringing the Newtonian universe into the very microcosm of domestic life. While engineering became an exclusively male preserve, scientific knowledge slowly entered the mental universe of highly literate women and girls.

Most public lecturing quickly came to include electrical experimentation. Already of considerable interest to Newton and to the other Fellows of the Royal Society, the phenomenon of electricity also just delighted and awed observers. In Britain Desaguliers was the most important electrical experimenter of his generation (in the American colonies it was his contemporary Benjamin Franklin). Desaguliers studied charges, conduction, attraction and repulsion of electrical particles, the effects of dryness and moisture. He distinguished between bodies that could be electrified and those that appeared naturally insulated from electrification except when suspended. He did not understand insulation, nor did many of his fellow practitioners in what could be a dangerous pastime. Following in his wake, by the second half of the century British electrical experimenters were using charges even in medical treatments of everything from lumbago to the gout. [74] The theoretical foundations for all these efforts to use electricity had been laid down in the queries to the *Opticks* (1723) where Newton had speculated on the properties of the aether, the miniscule effluvia that seemed to infuse nature and also seemed to be controlled by the universal principles of attraction and repulsion.

But Desaguliers was also more than an electrical experimenter and traveling lecturer. His linguistic and mathematical skills permitted him a wide variety of contacts abroad, and he translated into English from Latin a mathematical work by the Dutch Newtonian Willem s'Gravesande (pronounced skrave-san-da). S'Gravesande's *Mathematical Elements of Natural Philosophy, confirm'd by Experiments; or, An Introduction to Sir Isaac Newton's Philosophy* was one of the important eighteenth-century textbooks that made Newton's mathematics accessible and that also anchored the philosophical foundations of Western science on "evidence and stability which have put mathematics out of the reach of error and contention."[10] For its Dutch author, as for its English translator, this was an ethical and religious enterprise, intended, as its preface proclaimed, to show "that God is good, and that this appears also by mathematical demonstrations." God's goodness lay in the order and regularity of nature, now explicated mathematically. By the early eighteenth century the sensibility of a Dutch Newtonian like s'Gravesande was remarkably similar to that of other Newtonian Protestants. [81] The new science-inspired Protestantism spread throughout Continental Europe.

Like public lectures in England, s'Gravesande's much more technical account of Newtonianism, originally given in Dutch, also began with the atoms and with density and elasticity, then went on to calculate mathematically the force acting upon an inclined body: "Let the surface of the glass be AB; a particle C; this tends towards the glass in the line CD, perpendicular to the surface; it also tends towards the Point e . . . ." From a simple mathematical demonstration of attraction and repulsion in the straight-line motion of a drop of water on a glass surface, the text moves to a discussion of motion in general, the force of gravity, the vacuum experiment to illustrate the effects of gravitational force on bodies without resistance, then on to levers, weights, and pulleys. To these experiments "mechanical arithmetick" is added, and arithmetic along with geometry is used to calculate the power of machines.

Eventually Newtonianism subjected all nature to mathematical treatment: "The water that runs by its own gravity, in a channel open above, is called a river." So began s'Gravesande's mathematical explication of hydrostatics, the mechanical practices so necessary for canal building and the control of water pressure. By the end of his text the mathematician, although by a more technical and theoretical route, has also become a civil engineer.

As part of his professorship in Leiden s'Gravesande acted as a consultant on water projects in the Dutch Republic. In his youth he was also the member of a secret club that put out the first journal published

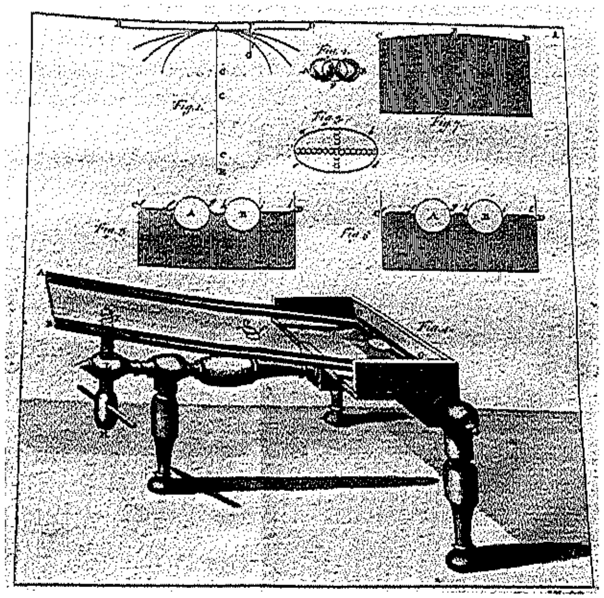


FIGURE 2.5 The illustration for the simple motion of a flat body on an inclined plane, from W. J. s'Gravesande's *Mathematical Elements.* Courtesy of Van Pelt Library, University of Pennsylvania.

in French (but outside of the control of French censors) that disseminated Newtonianism to French-speaking Europeans. The *Journal litéraire* emanated from the Dutch Republic and it flourished for only about a decade; it was over by the mid-1720s. Yet its influence spread deep into Europe and its colonies; south of the Alps Italian intellectuals like Celestino Galiani acted as corresponding editors. Early in the 1720s a European merchant in the distant Dutch slave colony of Surinam could write to one of s'Gravesande's co-editors and tease him by saying, "I will abjure my Cartesianism if you will adjure your Newtonianism." Desaguliers, s'Gravesande, Hauksbee, and a half dozen other early Newtonians, at work in lecture rooms, print shops, and editorial boards, had succeeded in spreading their master's science along with the Newtonian version of natural religion wherever European trade and empire had also penetrated. Newton's legacy became distinctively Western and undoubtedly contributed to the sense of superiority that sanctioned European wealth and overlooked the misery of others.

Dutch pupils of s'Gravesande took his ideas to other universities and academies in the Republic, while the French-language press sent them

far and wide. French was the international language of the age. Even English students learned Newtonianism from s'Gravesande in Leiden and then brought the knowledge back to Britain. In addition, the greatest doctor of the age and a professor of medicine at Leiden, Hermann Boerhaave, also took up Newtonian principles to describe the life of the body as dominated now by the principles of attraction and gravitation. As a practicing doctor Boerhaave was impressed by the experimental, practical side of the Newtonian style; it further reinforced his insistence upon hands-on observation and examination. In Leiden he became famous as the doctor who cared enough to venture into the homes of the sick and poor, to study disease as it was lived.

Boerhaave was quite simply the most important medical practioner of the age, and his practices became the norm in most medical schools by the middle of the century. [88] The greatness of medicine at Edinburgh derived from the years that its faculty had spent as students with Boerhaave in Leiden. By the middle of the eighteenth century, the extent and range of European domination enjoyed by Newtonian science, both practical and conceptual, had become wider and more sophisticated than even Newton—master experimenter as well as conceptualizer of space and time—could ever have imagined.

Thus no longer clerical, many Newtonians became worldly and cosmopolitan experimenters and showmen. S'Gravesande never took clerical orders, while in the case of Desaguliers being a clergyman was even something of a hobby. Although they paid his salary, preaching and caring for souls did not much interest him. One of his aristocratic patrons, for whom Desaguliers acted as an engineering consultant on his estates, became so incensed by Desaguliers's neglect for his parish that he sent this rebuke: "The inhabitants . . . have been forced to go a begging to other minsters to bury their dead. This is very shameful neglect." [76:219] When the great contemporary satirist William Hogarth did a popular engraving called *The Sleeping Congregation,* the preacher giving the sermon was widely regarded as none other than Jean Desaguliers.

In a bad poem (it is at least for us interesting) Desaguliers used Newtonian imagery to celebrate the coronation of George II (1728). *The Newtonian System of the World, the Best Model of Government* (p. 17) summed up his understanding of the new postrevolutionary relationship between English government and Newtonian science:

What made the Planets in such Order move,
He said, was Harmony and mutual Love.
The Musick of his Spheres did represent
That ancient Harmony of Government

Although Newton had little use for poetry, it was nevertheless a blessing that he died the year before the poem was published. Newton did not imagine that God had placed universal gravitation in the universe in order to glorify the institutions of mere mortals, even of kings.

By the end of the first quarter of the eighteenth century a far more secular understanding of history and time had come to prevail. Ironically Newton's science had helped to usher in an expansive and optimistic age in which he would have been a relative stranger. When Voltaire came to London in the mid-1720s he was stunned by the spread of Newtonian ideas, by the relative freedom in publishing and politics, and by the ease with which the literate classes seemed to socialize with one another. By ease he meant that the English aristocracy willingly fraternized with their lessers. Indeed, in Voltaire's mind all three phenomena were of a piece, and he told the world about it in his *Letters on the English Nation* first published in French in 1733. England was modern because Newton's science was better, its cultural life thrived on freedom, and its aristocracy respected men of learning and commerce. With wit and sarcasm Voltaire gave voice to the Anglophilia of the age, and his book was the single most important work of the century that introduced Newton's name and his principal achievements to Western readers. Voltaire added to its impact by publishing his own, rather technical exposition, *The Elements of Newton's Philosophy* (French edition pirated in 1738; Voltaire's approved edition, 1741).

With supporters like Voltaire (who was a deist), perhaps we can better understand why by the late-eighteenth-century Methodist ministers raved against Newton, calling him an ignorant pretender. Even John Wesley himself, the founder of Methodism, was ambivalent about the meaning of Newtonian science. For people who wanted Protestantism to be biblically based and from the heart, not the head, the Newtonian version of Protestantism seemed effete, a sop to the decadent mores of the rich or wellborn. Late in the century William Blake, the great radical, religious mystic, and prophet against empire, saw Newton as a symbol of human beings enslaved to material things, the creatures of science rather than the creators of new worlds. Science had become irretrievably associated with indifference, if not hostility, toward religion. The Whig oligarchy that so impressed Voltaire had helped to make liberal Christianity seem like a fig leaf to cover their greed and corruption.

Other radical critics of the age took up science not to encourage complacency but to undermine centuries of traditional belief and the power of the clergy. Man the machine, rather than man the sinner, became a metaphor of choice for atheists and materialists. Trained in science, they were capable of writing books with titles like *L'Homme machine* (1748) wherein all human action and emotion were seen to result from the movement of nerves and muscles. The metaphor horrified Newtonian as well as Christian critics, and it did not help that the author of *Man the Machine*, Julien Offray de La Mettrie, had been a student of medicine with Boerhaave in Leiden. [86] The Dutch publisher of the book had to write a book himself explaining that he did not endorse the ideas he published but did believe in freedom of the press. [82] When the English republicans like John Toland took Newtonian force and attached it to matter, just as Newton feared would happen, they invented a new and virulent form of materialism that influenced European and American thinkers as important as the French philosophes, Denis Diderot, the Baron d'Holbach, and Thomas Paine. The radical side of the European Enlightenment owed as much to Newtonian natural philosophy as did the moderate, more Christian side of this new cultural movement. Inspired by nature as revealed through science, radicals like Paine called for a philosophical religion that would encourage democracy.[11] None of the early Newtonians would have approved.

Even less radically materialist or pantheist philosophers imagined that mechanics stood as a model for making all human systems into sciences. Western thinkers had always appealed to nature for imagined laws to govern behavior; now they argued that morality itself might be reduced to "a system as well connected, as those of geometry, for example, or mechanics, and founded on as certain principles."[12] Despite the association with atheism and materialism, some theologians found in the machine the metaphor for divine design, a symmetry found in watches, hydraulic machines, wheels, even in the parts of the human body. At the end of the century, when searching for a new science of society, William Paley triumphantly proclaimed that "in the works of nature we trace mechanism; and this alone proves contrivance"—by the Divine Artificer. [26] Paley had been directly inspired by the industrial machinery that by the 1790s was increasingly visible in the English countryside. The popularity of the design argument was as old as Richard Bentley, indeed older, but now late in the eighteenth century industrial machinery gave it a new lease on life.

Thanks to the publicity generated decades earlier by Desaguliers and others, by midcentury mechanics as well as mechanisms of every size and description had become everywhere fashionable, and automata fascinated both the great and the lowly throughout northern and western Europe. Imagine an automaton musician playing a flute, a metal duck eating, drinking, and defecating (then picking its feathers), and another machine dressed like a dancing shepherd and playing a tabor and pipe. "I forgot to tell you, that the Duck . . . makes a gurgling noise like a real living Duck." Or so Desaguliers's translation of the lectures of the French mechanist Vaucanson told its readers. "The inspection of the machine will better shew that nature has been justly imitated," right down to the wings. The thing did not fly, but it did not take great imagination to ask, Why not? Throughout Europe the machines were presented along with learned but simple treatises that explained the underlying principles: "All these vibrations of the mouth may be performed . . . because the wind . . . must always be so regulated . . . it will have vibrations equal to those that are produc'd in the middle of the note where the sound increases in force, because it will be communicated to a greater quantity of air."[13] The fad for automata had nothing directly to do with Newtonianism, but the fashion assisted in the assimilation of Newtonian understandings of both the universe and local motion. It also helped to naturalize machinery from simple button makers to steam engines.

By the middle of the eighteenth century European children of some affluence were being taught to think mechanically while their parents, first men and then gradually women, were attending lectures in Newtonianism. [70] This European trend had started, however, in England a full generation earlier. Even the philosopher John Locke, as early as the 1690s, had written a simple treatise on natural philosophy for one of the wealthy pupils in his charge. There is some evidence to suggest that Newton gave him a hand with it. Decades later the manuscript treatise for children was partially copied in a popular science book, *The Philosophy of Tops and Balls*, published by one "Tom Telescope." [2] The only surviving diary written by an eighteenth-century adolescent tells us that in the Dutch Republic of the 1790s a boy of affluent parents routinely attended scientific lectures and read books about science and natural religion.[14]

Decades earlier in Paris, the equivalent of the weekly wage of a young worker got someone into a concert of flute music played by an automaton. In 1738 thousands paid to hear it. Vaucanson, the flutist's creator, made his money and quickly turned his attention to industrial machinery. In France, as elsewhere, applied mechanics was the route to profit and social prestige. Yet in France public lectures were nowhere near as popular and hence lucrative as they were in England. In Paris the abbé Nollet imitated Desaguliers and made a living with his lectures, but the professors at the Sorbonne were hostile to him and even put pressure on the authorities to close him down.

Nollet's textbook in mechanics was far more successful than his Paris lectures, and it was widely used in French engineering schools by the

middle of the century. By then most French engineers knew Newtonian mechanics, but almost to a man they were employed by the state, as befit their aristocratic origins. As we shall see shortly, the strength of French science lay not in its widespread availability but in mathematical originality as well as in theoretical innovations. These took Newtonian science in new and exciting directions. But on either side of the English Channel, being au courant with mechanical science, however superficially, signaled appreciation for innovation and modernity. No wonder that Queen Caroline decorated her garden with busts of Newton, Samuel Clarke, and Robert Boyle, among others. The first scientific society for, and organized by, women was established in 1785 in the Dutch city of Middelburg and used Nollet's textbook as a teaching manual.

The Newtonians of Desaguliers's generation and beyond offered, as Benjamin Martin said, nothing less than "utility, pleasure, and happiness" to their age. Showmen with lofty as well as practical messages, sometimes self-educated, found careers as itinerant lecturers. [24] They brought the Enlightenment out of the drawing rooms of the elite and to the middling classes, proclaiming science the key to human progress. Through mechanics in particular, Martin said, "we have here opened to our minds the wondrous laboratory of nature, and the stupendious processes therein carrying on, unheeded and unthought of by the vulgar." [54] Even earthquakes, volcanoes, and comets, although dangerous and destructive, were no longer "secrets in the school of natural philosophy." In addition, it was claimed, every mechanic and manual trade could be improved by Newton's science. Now applied science promised self-improvement, profit, and status.

Mechanical knowledge became one key to social mobility, and lecturers such as James Ferguson went up and down the English countryside telling of their life histories and the prosperity that came their way through scientific knowledge. [55] There was truth in the boast that applied science was one way up to a respectable living. Even in Newton's lifetime Francis Hauksbee, who had made some of the earliest electrical experiments seen at the Royal Society, had had no formal education and was a draper turned instrument maker and physics lecturer. In the early eighteenth century his writings were even known in Italy, while in the 1780s a Dutch instrument maker in Zeeland built a planetarium using a translation of Ferguson's lectures. Benjamin Worster, a friend of Desaguliers, lectured in bookshops, Masonic lodges, and academies for craftsmen and reached artisans, merchants, and tradesmen, any one of whom could have understood his clear and simple rendering of natural philosophy, mechanics, the laws of motion, and hydrostatics.

But the spread of science and opportunities for scientists, however