EUROPE 1450 TO 1789

ENCYCLOPEDIA OF THE EARLY MODERN WORLD

Jonathan Dewald, Editor in Chief

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nalists Descartes, Spinoza, and Leibniz; volume 5 covers the British empiricists from Hobbes through Hume; and volume 6 covers the French Enlightenment and Kant.

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THOMAS HOLDEN

PHYSICS. Physics, as a structured mathematical and experimental investigation into the fundamental constituents and laws of the natural world, was not recognized as a discipline until late in the early modern period. Derived from the Greek word meaning 'to grow', in ancient and medieval times "physics" (or "natural philosophy") was concerned with the investigation of the qualitative features of any natural phenomena (psychological, chemical, biological, meteorological, etc.) and was often guided by the metaphysical and epistemological tenets set out in the physical books of the Aristotelian corpus. These included the idea of the cosmos as a finite sphere in which no void or vacuum could exist, the division between the sublunary and celestial realms (each with its own types of matter and motion), the doctrine of the four sublunary elements (earth, air, water, and fire, each naturally moving either upward or downward), and a complex causal theory according to which any natural change requires the interaction of an agent that initiates the change and a patient that undergoes the change. As with many of the developments of the early modern period, modern physics defined itself in reaction to these received Aristotelian ideas.

This is not to say that Aristotle did not go unchallenged until the early modern period. In Hellenistic times, for example, Aristotle's theory of natural motion was seen to need supplementation since it could not explain satisfactorily why a thrown object continued in projectile motion once separated from the cause of its motion (for example, a hand) instead of immediately resuming its natural motion downward. The concept introduced to explain this was impetus—a propelling, motive force transferred from the cause of motion into the projectile. Similarly, atomism posed a long-standing challenge to Aristotelian matter theory. According to atomism, the universe consisted of small material particles moving in a void, and all natural change could be explained by the particles coming together and separating in various ways.

The challenges reached their climax in 1277 as Archbishop Tempier of Paris issued a condemnation that forbade the teaching of Aristotle as dogma. Although other criticisms of Aristotelian philosophy continued through the fourteenth century and after, the basic Aristotelian ideas regarding the nature of motion and the cosmos persisted in European schools and universities well into the seventeenth century, albeit in Christianized forms. The critical treatments of Aristotelian philosophy became the seeds from which modern physics grew.

Many other social, economic, and intellectual events also were responsible for the birth of physics and modern science. The Reformation and its consequent religious wars, the voyages of exploration and exploitation, the rise of capitalism and market economies, and the geographical shift of power from the Mediterranean basin to the north Atlantic were of particular import. In a somewhat controversial fashion we might characterize these influences as promoting a social, economic, and intellectual sense of insecurity among the people of Europe and contributing to a concomitant rise in entrepreneurial and epistemic individualism. One important result of this was an increased skepticism both as an everyday viewpoint and, as in Michel de Montaigne's (1533–1592) case, a full-blown skeptical theory.

The rise of printing is particularly important among the cultural changes leading to the birth of physics. The printed text allowed for wider distribution of recently resurrected and translated ancient texts on philosophy and mathematics. Euclid's (fl. c. 280 B.C.E.) *Elements,* for example, was published in numerous modern editions, and the pseudo-Aristotelian *Mechanics* and the works of Archimedes (c. 281–212 B.C.E.) were brought to the Latin-educated public. These works formed the basis of the mixed or middle sciences (being both mathematical and physical) and provided the disciplinary form into which the new physics would fit. The use of diagrams and illustrations as teaching and learning devices was crucial to this revival of applied geometry. Books also allowed for a standardization of material that enabled widely dispersed individuals to study the same texts of classical and modern authors. In the sixteenth century, publications of how-to-do books and pamphlets brought mathematics and concerns about mechanical devices to a much broader public, including artisan and nonuniversity classes. However, the practical inclination toward mechanics was given theoretical credence by the anti-Aristotelian theory of atomism (reinvigorated in the Latin West by the early-fifteenth-century recovery of Lucretius's [c. 95–55 B.C.E.] *De rerum natura* [*On the nature of things*]) and philosophical criticisms of Aristotle's theory of causality, which took mechanical devices as exemplars of phenomena for which Aristotle's theory could not properly account.

The increased focus on the workings of the natural world led to the institution of societies dedicated to scientific learning. In 1603, for example, the Academy of the Lynxes (Academie dei Lincei) was founded in Naples by Prince Federico Cesi (1585–1630). In 1662, the most influential of the new institutions, the Royal Society of London, was founded by Charles II of England (ruled 1660–1685). The society encouraged Christian gentlemen to study natural philosophy, held regular meetings, and published its proceedings. The Royal Society proved a venue for many amateurs to pursue science and may have created the first professional scientist by hiring Robert Hooke (1635–1703) as its curator of experiments.

THE NEED FOR A NEW THEORY OF THE NATURAL WORLD

The general attacks on the Aristotelian view of nature gained momentum through the pressing need to solve a set of particular physical problems that were largely intractable given Aristotelian premises. In particular, demand for a revision to Aristotelianism was brought to crucial focus by Nicolaus Copernicus's (1473–1543) publication of *On the Revolutions of the Heavenly Spheres* in 1543. In it, Copernicus laid out an astronomical system based on circles and epicycles much in the same mathematical vein as Claudius Ptolemy's (c. 100–170), but shifted the sun to the mathematical center of the earth's orbit and made the earth move in a threefold manner (daily, annual, and axial motion to account for precession). The theoretical shift left a major conceptual problem for Copernicus's followers: namely, how to reconcile a physical description of the universe with Copernicus's new mathematical description of it. In particular, it became problematic to talk about the motion of bodies on earth if the earth itself was moving and also to account for the motion of the earth itself. Tycho Brahe (1546–1601) was one of the first to worry about physical cosmos, and based on his own marvelous celestial observations, devised his own compromise system. But Tycho's system was qualitative and never put into good mathematical shape, and, therefore, useless to professional astronomers. Nevertheless, his work on comets did away with the crystalline spheres in which planets were thought to be embedded.

The first to successfully challenge Aristotle on his physics, matter theory, and cosmology—and, in the process, vindicate Copernicus—was Galileo Galilei (1564–1642). Galileo was trained by artisans, and after dropping out of medical school, began to work on problems of mechanics in an Archimedian manner, modeling his proofs on simple machines and floating bodies. Contributing to Galileo's confidence in the Copernican system was the construction of his own telescope in 1609 (one of the first) and his consequent investigation of the moon, the sun, the Milky Way, and the discovery of four moons of Jupiter. These investigations were published in *The Starry Messenger* in 1610 and in the *Letters on the Sunspots* in 1613. They affirmed Galileo's conviction that the earth was a material body like the other planets, and that Copernicus's system was an accurate physical description of the universe. But he still lacked an account of how bodies moved on an earth that was itself moving.

Galileo's most influential book, *Dialogues concerning the Two Chief World Systems* (1632), was his most elaborate defense of Copernicanism. In this book he argued most effectively that a theory of motion for a moving earth was not only possible but more plausible than the Aristotelian theory of motion. Specifically, he argued for a form of natural motion (inertia) where bodies moved circularly, and for the principle of the relativity of observed motion (which had been used before by Copernicus and others). This allowed him to claim that the motion of the earth was not perceptible since it was common to both the earth and bodies on it. At the end of the *Dialogue,* he thought he proved Copernicanism by claiming the earth's trifold motion could physically explain of the tides.

Galileo's condemnation for heresy under the papacy of his former friend Urban VIII was based on the *Dialogue;* he was put under house arrest for the rest of his life. During this time, he began work on his final publication, *Discourses concerning Two New Sciences* (1638). This work revived the Archimedean, mechanical physics he had virtually completed between 1604 and 1609. Here he argued for a one-element theory on which matter was to be understood solely by its mechanical properties, as Archimedean machines were understood, and for a theory of motion on which motion was essentially related to time. Particularly, he argued that falling bodies accelerate in proportion to the square of the time of their fall, and provided experimental evidence for this by measuring balls rolling down inclined planes. The emphasis on time as the important independent variable occurred to him from discovering the isochrony using pendulums, whose isochrony he discovered. As Galileo was working out the details of a new physics, Johannes Kepler (1571–1630) formed the world's first mathematical astrophysics. It was he who finally abandoned the principal assumptions of Ptolemaic and Copernican astronomy by introducing elliptical motion and demanding that astronomical calculation describe real physical objects. Although to his contemporaries Kepler was mostly known for producing the most accurate astronomical tables to date, his legacy lies in a reorientation of astronomy away from a predictive discipline aimed at mathematically "saving the phenomena" to one that combines observational predictions (how the planets move) with physical theory (why they move). For example, Kepler offered not only his so-called three laws describing planetary motion, but also answered the causal Copernican problem by explaining that the planets were moved by a quasi-magnetic force emanating from the sun that diminished with distance and were hindered by their natural inertia or "sluggishness." His integration of underlying physical mechanism and descriptive law, much in the same manner as Galileo's, was to become a hallmark of seventeenth-century science. It is in this sense that both thinkers built the foundation on which the mechanical philosophy was to rest.

THE NEW SYSTEMATIZERS

Although Galileo's and Kepler's works were complementary, neither thinker attempted to reformulate the whole of the Aristotelian natural philosophy. René Descartes (1596–1650), on the other hand, attempted to build a complete system to replace Aristotelianism and put philosophy, including natural philosophy and the science of motion, on a firm epistemic and theological basis (the Cartesian *cogito*—I think therefore I am—and that God is no deceiver; *Meditations on the First Philosophy,* 1641). Regarding motion, he shifted emphasis from Galileo's machines to collision laws and promulgated a version of straight-line inertia. Descartes's laws of collision combined with a belief in a corpuscular (if not strictly atomic) matter allowed him to consider many physical problems in terms of material contact action and resulting equilibrium situations. For example, Descartes attempted to account for planetary motion and gravity in terms of vortices of particles swirling around a center, pushing heavier particles down into the vortex while carrying others around in their whirl. The Cartesian program was laid out in its most complete form in *The Principles of Philosophy* (1644). There he used the vortex theory and the strict definition of place to placate the church and to show that Copernicanism was not literally true. Descartes hoped this book would become the standard text at Catholic schools, replacing even Thomas Aquinas, but it was placed on the Index of Prohibited Books in 1663.

Descartes's followers could be called "mechanical philosophers," though in fact the phrase was coined later by Robert Boyle (1627–1691). Most notable among them was Christiaan Huygens (1629–1695), who, apart from making several important astronomical discoveries (for example, the rings of Saturn and its largest moon, Titan), published works on analytic geometry, clockmaking, and the pendulum, and corrected Descartes's erroneous laws of collision. Huygens's laws were proven by using Galileo's principle of relativity of perceived motion in *On Motion* (published in 1703; composed in the mid-1650s). He forcefully championed Cartesian philosophy in his criticisms of Isaac Newton's (1642–1727) notion of gravity, rejecting it as a return to occult qualities and offering instead his own aetherial vortex theory in *Discourse on the Cause of Heaviness* (1690).

In England, Robert Boyle emerged as the most vocal champion of the new philosophy. Boyle wrote prolifically on physics, alchemy, philosophy, medicine, and theology, and approached all with a single and forcefully articulated mechanical worldview, though in practice he seldom rigorously applied it. For Boyle, all natural phenomena were to be studied experimentally, and explanations were to be given by the configurations and motions of minute material corpuscles. Boyle's writings either argue for this view generally—for example, *The Origine of Formes and Qualities* (1666)—or by example, for example, *New Experiments Physico-Mechanicall, Touching the Spring of the Air and Its Effects* (1660). In the *Origine,* for example, Boyle argues against the Scholastic reliance on substantial forms, holding these to be unintelligible in themselves and useless for practical purposes. Instead he offers explanation using analogies for natural processes that were already well worn: that of the lock and key and that of the world as a clock. Boyle's criticisms were widely circulated both in England and on the Continent. (It is of note that Robert Hooke's work on springs was more rigorous and his version of the mechanical philosophy in terms of vibrating particles was later

Physics. *Experiment with an Air Pump,* 1768, painting by Joseph Wright of Derby. NATIONAL GALLERY, LONDON, U.K./BRIDGEMAN ART LIBRARY to become more widely used than Boyle's.) Boyle, like some other seventeenth-century thinkers, was deeply committed to the use of mechanical science to further belief in God. This fact is important to note, as no great schism was felt in the seventeenth century between the findings of science and belief in the deity, although the charge of atheism was often leveled in battles between competing scientific schools, particularly against Thomas Hobbes (1588–1679), who may be the most coherent of all the mechanical philosophers, and who had the widest philosophical impact during the mid-century.

THE NEW PHYSICS

If the systematization of these modes of thought and physical problems into a coherent whole can be attributed to one man, it is Isaac Newton (1642–1727). In his *Mathematical Principles of Natural Philosophy* (1687), Newton combined the study of collision theory, a new theory regarding substantial forces and their the measure, and a new geometrical version of the calculus to draw consequences regarding motion both on earth and in the heavens. The book begins with the three laws of motion: the law of inertia, the force law, and the law of action and reaction. Although the law of inertia was first framed by Descartes, the latter two laws were Newton's stunning innovations. Of particular importance is the second law, in which Newton introduces a novel measure of force akin to the modern notion of impact (instantaneous change in momentum). Considering force in this way, Newton was able to treat the effect of any force as if it were the result of a collision between two bodies, thus reducing the variety of physical phenomena to cases of collision.

In general, the evolution of the concept of force in the seventeenth century constitutes a crucial feature in the birth of modern physics. At the beginning of the century, the term "force" was used with a variety of intuitive meanings. Lack of a precise concept was due, in part, to the fact that characterizations of force were derived from analyses of several different physical situations: equilibrium situations in terms of the law of the lever (where a specific weight was related to the force required to balance it), impact in collisions, and free fall. It was unclear how to relate these, which were all by the Aristotelian tradition violent motions, that is, against a body's natural inclination. With Descartes's formulation of the principle of inertia, the mechanical analogue of Aristotelian natural motion, force came to indicate the cause of any deviation from (seemingly natural) inertial motion. By further fixing its meaning in all cases, Newton was able to provide a unified treatment of the physical situations mentioned above.

Newton also showed that the Cartesian explanation of planetary motion by an aetherial vortex was untenable. Moreover, using Kepler's laws and a host of other planetary observations, he demonstrated that the planets must be drawn toward the sun (as well as toward one another) by a force inversely proportional to their distance and directly proportional to their mass: by a gravitational force. This was Newton's most contentious discovery. Although his laws of motion were quickly recognized as correct, Newtonian gravitation, was dismissed by many as a "fiction" and a "mere hypothesis." Put differently, since the gravitational force did not rely on the collisions or springs endorsed by mechanical philosophers, Newton's contemporaries perceived it as a return to recently banished occult Aristotelian properties. In general, since force (gravitational or otherwise) is not a directly perceivable property of matter, it seemed Newton was rejecting a mainstay of the mechanical philosophy by admitting ontologically gratuitous terms into his physical explanations. (George Berkeley [1685–1753] would try to recast Newtonian mechanics without force in his *On Motion* [1721].)

Newton's most powerful critic in this and other regards was Gottfried Wilhelm Leibniz (1646–1716). Although their antagonism originated with a priority dispute in the mid-1690s over the invention of the calculus—which Newton and Leibniz had actually invented independently—it ended with Newton's anonymous writing of the official opinion of the Royal Society in which it was declared that he, Newton, was the true originator. This tiff was continued in a protracted epistolary debate between Leibniz and Newton's disciple, Samuel Clarke (1675–1729), over the metaphysical and religious implication of Newtonian physics. Leibniz claimed that Newton's theory of gravitation not only did not explain anything (since the notion of gravitational action-at-a-distance was itself unintelligible), but promoted atheism. The other key debate was over the nature of relative versus Newtonian absolute space. Similar debates between Newtonians and their detractors regarding the explanatory and theological significance of universal gravitation were to color the philosophical landscape well into the eighteenth century.

Most importantly, however, Newton's debates with Leibniz yielded Newton's most explicit characterizations of his scientific method, which were to serve as a basis for all later science. In warding off criticism, Newton often insisted that the notion of universal gravitation was not in the least hypothetical, but was securely and positively based on empirical evidence. His insistence that theoretical claims should be justified only by observations, even when dealing with properties not directly perceivable, contradicted the idea of some of his contemporaries, who were accustomed to deducing theoretical claims from higher-level metaphysical or theological principles. The reliance on observation and experiment, more than any of Newton's particular claims, quickly became a hallmark of science as a whole. The Royal Society, increasing professionalization, an experimental method, and a set of unique problems all testify to physics' emergence as its own discipline during the latter half of the seventeenth century.

RECASTING PHYSICS

Curiously, despite its numerous innovations, Newton's work was mostly written in an older geometrical style, not the differential calculus. The move away from geometry—which had dominated mathematical thinking since antiquity—was not completed until the middle of the eighteenth century, well after Newton's death, although it had begun in the early years of the seventeenth century with the work of François Viète (1540–1603), Thomas Harriot (c. 1560–1621), Descartes, and Pierre de Fermat (1601–1665) on infinitesimals and the algebraic treatment of curves. This new analytical treatment of mathematics was the cause of aforementioned dispute between Newton and Leibniz regarding the calculus: while Leibniz's version of the calculus was based on the algebraic techniques gaining strength at the time, Newton's version (at least as published during his lifetime) was a geometrical analogue. Leibniz's version was eventually adopted, and by the mid-eighteenth century, virtually all developments of the calculus were undertaken in an algebraic style. The culmination of this movement was to come in Leonhard Euler's (1707–1783) *Mechanics or the Science of Motion Exposited Analytically* (1736) and Joseph-Louis Lagrange's (1736–1813) *Analytical Mechanics* (1788).

Finally, it remains to remark that Newtonian physics and Newton himself, by name if not by precise deed, was taken as exemplary for the age that followed. Numerous works for children and women, now thought fit for education, appeared in many languages; among such were E. Wells, *Young Gentleman's Course in Mechanicks, Optics, and Astronomy* (1714) and Francesco Algarotti's (1712–1764) *Sir Isaac Newton for Use of Ladies* (1739). More serious discussions and popularizations of Newton and his work were also numerous. To mention only a few, we find in the early eighteenth century John Theophilus Desagulier's (1683–1744) *Course of Experimental Philosophy* (1744), Willem Gravesande's (1688–1742) *Mathematical Elements of Natural Philosophy* (1721), Henry Pemberton's *View of Sir Isaac Newton's Philosophy* (1728), and most impressive of all Colin Maclaurin's (1698–1746) posthumously published *An Account of Sir Isaac Newton's Philosophy* (1748). In France Newton also had his fame; Pierre Louis Moreau de Maupertuis (1698–1759) taught Newtonianism to Voltaire (François-Marie Arouet, 1694–1778), and to Madame du Chatelet (1706–1749), leading Voltaire to write the popular *Elements of Newtonian Philosophy* (1741), which is perhaps the best known but certainly not an isolated instance. Newton was seen during this time as the man who had brought modernity (and perhaps salvation) to England and to the world. The prevailing thought of the times was well summed up by Alexander Pope in his "Epitaph Intended for Sir Isaac Newton":

> Nature and Nature's laws lay hid in night;
> God said, "Let Newton be!" and all was light.

See also **Academies, Learned; Astronomy; Berkeley, George; Boyle, Robert; Brahe, Tycho; Catholicism; Copernicus, Nicolaus; Descartes, René; Galileo Galilei; Huygens Family; Kepler, Johannes; Leibniz, Gottfried Wilhelm; Mathematics; Montaigne, Michel de; Newton, Isaac; Philosophy; Reformation, Protestant; Scientific Method; Scientific Revolution.**

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PETER MACHAMER AND ZVI BIENER

PHYSIOCRATS AND PHYSIOCRACY. Physiocracy was an economic theory that flourished in France in the second half of the eighteenth century, and an important example of Enlightenment social science. In 1757 François Quesnay (1694–1774), the chief theorist of Physiocracy, met Victor Riqueti, marquis de Mirabeau (1715–1789), initiating a lifelong collaboration. Two years later, Quesnay published his *Tableau œconomique,* a work he and Mirabeau regarded as the foundation of Physiocracy. This was followed by Mirabeau's *Théorie de l'impôt* in 1760, and the *Philosophie rurale,* the first full exposition of physiocratic thought, in 1763. In the 1760s, Mirabeau and Quesnay recruited Pierre-Samuel Dupont (1739–1817), Guillaume-François Le Trosne (1728–1780), Nicolas Baudeau (1730–1792), J.-N.-M. de Saint-Péravy (1732–1789), and Paul-Pierre Le Mercier de la Rivière (1719–1801); the latter published the most complete account of the doctrine in his *L'ordre naturel et essentiel des sociétés politiques* (1767). Physiocracy also won converts in Sweden, Germany, Austria, and Italy, and Le Mercier de la Rivière traveled to Russia to consult with Catherine II the Great (ruled 1762–1796).

Physiocracy addressed critical problems of the French state in the aftermath of the Seven Years'