any case, Descartes developed a lung inflammation from which he soon expired on 11 February 1650. The queen's attempt to inter him with great honor in Sweden was opposed by the French ambassador. Sixteen years after his death, his remains were conveyed to France for interment among his countrymen.

See also DESCARTES'S MECHANICAL COSMOLOGY; NEWTONIAN COSMOLOGY

[B.S.B.]

Further Readings

Baillet, Adrien (1693) The Life of Monsieur Des Cartes. London: R. Simpson.

Bell, E.T. (1937) Gentleman, soldier, and mathematician: Descartes. In Men of Mathematics. New York: Simon and Schuster.

Boyer, C. (1959) The Rainbow. New York: Thomas Yoseloff.

Descartes, R. (1985) The Philosophical Writings of Descartes. J. Cottingham, R. Stoothoff, and D. Murdoch (eds.). Cambridge: Cambridge University Press.

Haldane, E.S. (1966) Descartes, His Life and Times. New York: American Scholar Publications.

Ruestow, E.G. (1973) Physics at Seventeenth-Century Leiden: Philosophy and the New Science in the University. The Hague: Nijhoff.

Sabra, A.I. (1967) Theories of Light from Descartes and Newton. London: Oldbourne Book Company.

Schuster, J. (1977) Descartes and the Scientific Revolution, 1618–1634: An Interpretation. University Microfilms International.

Sirven, J. (1930) Les années d'apprentissage de Descartes (1596–1628). Albi: Imprimarie cooperative du sud-ouest.

Vrooman, J.R. (1970) René Descartes: A Biography. New York: G.P. Putnam & Sons.

Williams, Bernard (1967) René Descartes. In Paul Edwards (ed.): The Encyclopedia of Philosophy. New York: The Macmillan Company and The Free Press.

Descartes's Mechanical Cosmology

René Descartes's celebrated assertion "je pense, donc je suis" (I think, therefore I am) is widely acknowledged as the starting point of modern philosophy. What is less often recognized is that Descartes was the first modern cosmologist; his writings, principally *Le monde, ou traité de la lumière* (1633) and the *Principia philosophiae* (1644), signify the first attempt to bring a single set of principles to bear on terrestrial and celestial phenomena. Descartes's cosmological speculations have been overshadowed by the dynamical science of motion proposed by Isaac Newton, as well as by his own lasting contributions to modern philosophy. However, Descartes was the architect of a coherent and plausible cosmology that stood at the forefront of natural philosophy for the better part of a century and played a leading role in the demise of the deeply entrenched Scholasticism. Even Voltaire, who was often a harsh critic of Descartes, conceded in his *Lettres sur les Anglais* (1728) that Descartes "was valuable even in his mistakes. He deceived himself, but then it was at least in a methodical way. He destroyed all the absurd chimeras with which youth had been infatuated for two thousand years. He taught his contemporaries how to reason, and enabled them to employ his own weapons against himself. If Descartes did not pay in good money, he however did great service in crying down that of a base alloy" (Voltaire 1910, p.115).

Descartes's cosmology is founded on the conviction that nature is a machine. The idea of a world machine was not a seventeenth-century innovation. It can be discerned, for example, in the armillary spheres with which the medieval astronomer imitated the real celestial intelligences that transported the planets through the skies. With Descartes, however, this idea received a new and powerful expression: all natural phenomena, from the motions of celestial bodies to animal and vegetative life, are explicated in terms of the geometrical property of extension and its proper modes (size, shape, position, and the disposition of parts to be moved). What distinguishes Descartes's mechanical cosmology from similar views advocated by his mentor Isaac Beeckman, the English philosopher Thomas Hobbes, and the French savant Pierre Gassendi is that it attempts to restate substantive results in optics, astronomy, and mathematics in order to forge a foundation in physical theory for the Copernican hypothesis, which Descartes accepted on account of its simplicity and clarity (see

Descartes 1983, III.17). Although Johannes Kepler and Beeckman preceded him in advancing a physical basis for the Copernican system, Descartes's systematic approach to the various branches of knowledge enabled him to address the many scientific and philosophical issues raised by Copernicus's bold conjecture. Although he did not give to natural philosophy a form that it was bound to keep, Descartes, through the richness of his ideas, furnished his successors with a new set of problems and tools for their solution which, as Voltaire intimates, prepared the way for the dynamical cosmology that we now readily identify with Isaac Newton.

The Authority of Reason

As early as 1619, Descartes became convinced of the need for a complete reform of the sciences, one that would be sensitive to the interconnectedness of the various branches of knowledge (see DESCARTES, RENÉ). Aristotle had relied on logic as a way of unifying knowledge. While conceding that "logic does contain many excellent and true precepts," Descartes noted that "these [true precepts] are mixed up with so many others which are harmful or superfluous that it is almost as difficult to distinguish them as it is to carve a Diana or a Minerva from an unhewn block of marble" (Descartes 1985, vol. 1, p. 119). This state of affairs, Descartes contended, was responsible for the wrangling of the Schools. To provide a secure foothold for the reform of the sciences, Descartes turned to the methods of mathematics. It seemed to Descartes that mathematics was immune to controversy because it was built up step by step from principles that are clear and distinct to the attentive mind. As an expression of his ideal of the unity of knowledge, Descartes came to employ the metaphor of a tree of knowledge, with metaphysics constituting its roots, physics its trunk, and the other sciences (including ethics) its many branches.

Descartes spent the period from 1629 to 1633 preparing a comprehensive statement of his mechanical cosmology with the working title *Le monde*. Upon learning that the Congregation of the Holy Office had condemned Galileo's *Dialogo sopra i due massimi sistemi del monde* (*Dialogue Concerning the Two Chief Systems of the World*) in 1633 for advancing the Copernican hypothesis, Descartes elected to withhold his treatise (the better part of this work was published posthumously as two separate treatises, *L'homme* in 1662 and *Le monde, ou traité de la lumière* in 1664). "If it [the earth's motion] is false," Descartes confessed to the Minimite father, Marin Mersenne, "so are all the foundations of my Philosophy, since they clearly demonstrate this motion" (Adam and Tannery 1974, vol. 1, p. 272). For six years, Descartes avoided the subject of cosmology, even in his ample correspondence with Mersenne.

The year 1639 brought a change of heart. One factor was Descartes's discovery of the principle of the relativity of motion, which would enable him to retain the Copernican theory in substance, while rejecting it in name. A second factor was Descartes's belief that his explanations must be founded on principles that are as certain as the axioms of mathematics. These epistemological foundations were detailed in the *Meditationes de prima philosophiae* (1641), the work that asserted that any account of knowledge must start with the subjective conditions of human inquiry.

In the sixth and final meditation, Descartes remarks that although perception discloses a world of qualities, there is no necessity that the world itself be in any way similar to the one given in experience. If we seek to found the larger truths of physics on the narrower and more certainly established truths of mathematics, we must consult our intellect, which informs us that our sensations are produced by corpuscles of matter (differentiated solely by their size, shape, and motion), which produce sensations of qualities when they act on our nerves. We can imagine material bodies without hardness or weight. We can even conceive of bodies deprived of their ability to affect our senses. It is beyond our capacity, however, to conceive of a physical body that is not extended (cf. Descartes 1983, II.4). To describe this essential quality of matter, Descartes selected the passive principle, *extensio*. The notion of body involves other qualities such as hardness, weight, and color, but when we consider the matter carefully, we find that (as pertains to body) we cannot attach any distinct idea to these attributes. Accordingly, they are treated by Descartes as secondary qualities, or as explicable in terms of the primary quality of extension and its proper modes.

The complement of Descartes's mechanistic view of matter is an account of mind that firmly separates spirit and all sources of activity from nature. The essence of mind is the activity of thinking (*cogitatio*), understood broadly to include all forms of conscious activity. Critics like the English philosopher John Locke took Descartes to task for asserting that the mind thinks always, an implication obviously contradicted by certain features of our psychology. However, what Descartes meant to highlight by defining mind solely in terms of the activity of thinking is that mind does not play an activating principle in nature. An embodied soul can will motion for the body, but Descartes held that "we have no more reason to think that it is our soul which produces . . . the movements [of the body] . . . than we have reason to think that there is a soul in a clock which makes it tell the time" (Descartes 1985, vol. 1, p. 315). The vast majority of natural phenomena, from the vast whirlpools of matter that transport the planets to bodily functions, are never affected by the human will.

Having firmly distinguished two ontologically distinct kinds of substances, Descartes faced two sorts of problems, one concerning the relation of mind and body and a second, epistemological problem concerning how it is that mind knows matter. In his *Discours de la méthode* (1637) and in other places, Descartes suggests that our minds are created with innate "seeds of truth." Coming to know matter and its modifications involves drawing out the principles that are implicit in these cognitive seeds. Descartes is often interpreted as asserting that the mind is furnished with innate ideas, a view about which he shows no enthusiasm whatsoever. When pressed, he asserts that the mind has innate ideas only in potency, in the way that a person can be said to have a disposition to gout. Such analogies are not terribly revealing. We can affirm, however, that Descartes's doctrine of innate ideas signals, among other things, a rejection of the Scholastic conviction that understanding demands images furnished by the senses, a view that explicitly ruled out the scientific investigation of so-called occult phenomena or causes that are hidden from the senses, such as the virtue that causes magnetic attraction or cures sickness. In his writings, Descartes consistently defends the authority of reason. The authority of reason means for Descartes that there are *some* privileged truths of nature that cannot be discovered by the senses at all, which in turn will serve as the foundation for explanations of all natural phenomena (see Clarke 1988, p. 69).

Laws of Motion

These privileged truths are detailed in Part II of the *Principia philosophiae* (1644), a lengthy treatise that Descartes composed as a textbook to replace the standard texts based on the teachings of Aristotle. Descartes's *Principles* restates, though in a more studied manner, the central cosmological theses of his earlier treatise, *Le monde*. Natural phenomena are to be explicated in terms of the mobility of insensible particles of matter, according to principles that can be plainly understood. As a first order of business, Descartes rejects the ordinary idea of motion as "the action by which some body travels from one place to another" (Descartes 1983, II.24, p. 50). If we observe that as much effort is required to put a moving body to rest as is required to put a resting body in motion, we can see that the suggestion that motion requires an effort, whereas rest does not, is mistaken. It is therefore improper to treat motion and rest as different orders of being and to suppose that one needs more power to put in motion a body that is at rest than, conversely, to bring to rest a body that is in motion. "The truth of the matter," Descartes submits, is that motion "is the transference of one part of matter or of one body from the vicinity of those bodies immediately contiguous to it and considered as at rest into the vicinity of (some) others" (Descartes 1983, II.25, p. 51). Accordingly, motion is more appropriately conceived as a relational property (i.e., as the change of distance between bodies). Since it is always in contact with bodies that are immediately contiguous to it (i.e., the atmosphere), this definition enables Descartes to assert that the earth, properly speaking, does not move.

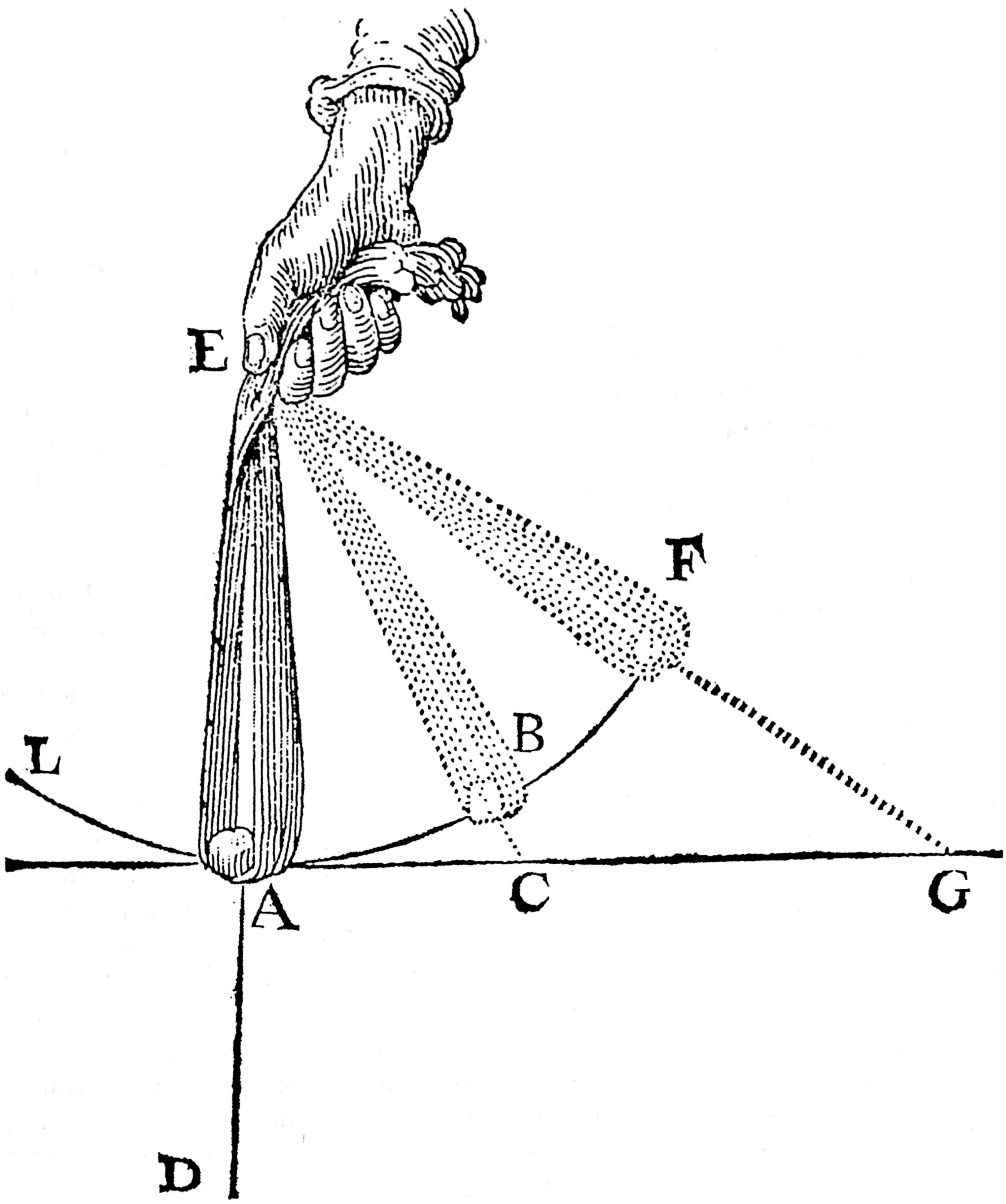
Motion has two causes, a universal and primary cause, and a particular cause that results in corpuscles of matter having some motion that they previously lacked. The universal cause is a law of conservation, which is justified by an appeal to God's nature, according to which God always acts in a consistent way, maintaining the same quantity of motion and rest that he put into the world when he first created it: "[I]t is one of God's perfections to be not only immutable in His Nature, but also immutable and perfectly constant in the way He acts . . . [I]t is completely consistent with reason for us to think that, solely because God moved the parts of matter in diverse ways when He first created them, and still maintains all this matter exactly as it was at its creation, and subject to the same laws as at that time; He also maintains in it an equal quantity of motion" (Descartes 1983, II.37, p.58). From a consideration of God's immutability, we can arrive at the knowledge of three laws or particular causes of the diverse movements of individual bodies.

The first law of nature asserts that "each thing, as far as is in its power, always remains in the same state; and that consequently, when it is once moved, it always continues to move" (Descartes 1983, II.37, p. 59). In the absence of external disturbances, all modes and attributes of matter are conserved from moment to moment in exactly the same state by God's creative concourse. If a particle is moving, it does not come to a stop of its own accord. By the same token, if a body is at rest, it does not simply start moving. This ontological equivalence of rest and motion is at the very heart of the new idea of motion fashioned by Descartes. Motion and rest are similarly positive states of bodies that are conserved in the absence of external actions.

The first law asserts the conservation of rest and motion as states of matter. It does not specify in what direction(s), if any, the bodies move. It is the second law of Descartes's *Principles* that gives the rectilinear nature of undisturbed motion its first explicit formulation: "that all movement is, of itself, along straight lines" (Descartes 1983, II.38, p. 60). The critical insight here is that rectilinear motion is the only direction that can be uniquely and completely defined at a given moment of time. It is therefore the only direction that can be conserved by God in exactly the same way as in the previous moment. Descartes recognized that motion does not take place in a moment of time. However, he reckoned that God conserves a body just as it is in the moment that it is preserved. If, as Kepler had asserted in his *Astronomia nova* (1609), curved motions are the privileged paths described by bodies, this would require that God concern himself with two successive moments of time, an implication that conflicts with the first law of motion. Indeed, if a body were to describe a curved path, this would indicate that some external cause has affected its inertial state. With the second law, Descartes dissolved the long-standing problem concerning the cause of motion, which sustained medieval impetus theories, and directed scientists to a problem that held the key to celestial dynamics: what causes changes of motion?

The two laws both rely on the conserving activity of God. Together they hold that God conserves a quantity of action that is determined in a unique direction and that is maintained from one moment to the next. Motion is therefore, on Descartes's account, a series of actions that occur at discrete moments of time. Moreover, this action at a moment of time is not the cause or reason of subsequent actions. Although Descartes is rightly credited with the law of inertia, the very foundation of the modern science of dynamics, motion in a straight line is not uncaused, as Newton will assert a half century later, but is supported by the conserving activity of God.

A consequence of Descartes's second law of nature is that "bodies which are moving in a circle always tend to move away from the center of the circle which they are describing" (Descartes 1983, II.38, p. 60). Article 39, Part II, of the *Principles* invokes the sensation that we have when we whirl a stone



Centrifugal force. In this illustration taken from the Principia philosophiae *(1644), the force of motion is described under two aspects. The stone tends to recede along the tangential line* (ACG) *at each moment it circulates about the center of rotation under the constraint of the sling, as specified by Descartes's second law of motion. However, the sling resists this tendency, which occasions a second effect, namely, an endeavor to recede radially along the line* AD *from the center of rotation* E. *It is this centrifugal endeavor that is the basis of Descartes's contention that light consists in the endeavor of corpuscles of the second element to recede from the center of rotation.*

in a sling in order to illustrate this centrifugal tendency of a body moving in a circle. The stone in the sling tends to recede along the tangential line *ACG* at each moment it circulates about the center of rotation, as specified by the second law of motion. The sling resists this tendency, however, which gives rise to a second effect, namely, an endeavor to recede radially along the line *AD* from the center of rotation *E*. If we consider only the part of the stone's motion that is impeded by the sling, we can say that the stone endeavors to recede radially from its center outward along a straight line, even though it is in fact impeded by the sling and describes a circle. It is this that explains Descartes's puzzling remark that "one and the same body can be said to tend to move in diverse directions at the same time" (Descartes 1983, II.55).

Although he is often portrayed as an arch-mechanist who attempted to fabricate the cosmos out of extension and motion alone, Descartes's analysis of the mechanics of circular motion testifies that he regarded force as a cause of the modal dispositions of bodies, distinct from motion and rest, and so as a real property of bodies (see Gabbey 1971, p. 9). However, since force is not held by Descartes to constitute the essence of matter, no systematic development of the notion of force is to be found in his writings. Furthermore, even if Descartes were to have granted the notion of force a more central place in his cosmology, his interest was restricted to force as that property of a body by virtue of which it acts on another body. Although his analysis of circular motion pointed to an external constraint that diverts a body from its inertial path, Descartes's conception of force did not point in the direction of Newton's dynamical theory (see NEWTONIAN COSMOLOGY).

Even so, Descartes's analysis of the mechanics of circular motion exerted a profound influence on the development of mechanics. Christiaan Huygens (and the young Isaac Newton) came to regard centrifugal force, in the manner of Descartes, as the manifestation in circular motion of the inertial tendency of bodies. Accordingly, Huygens's work embodies the conviction that centrifugal force is a real force of bodies, as opposed to our modern wisdom, which stipulates that it is something that depends on the frame of reference (see Meli 1990). In his *De vi centrifuga* (composed in 1659 and published posthumously in 1703) and in his *De horologio oscillatorio* (1673), Huygens advanced the mathematics of centrifugal forces in circular motion. In another paper, *Discours de la cause de la pesanteur* (1669), Huygens reasserted Descartes's thesis that gravity is the effect of the centrifugal force of a circulating fluid. This vortex, Huygens asserted, rotated seventeen times faster than a point on the equator, owing to the diurnal rotation of the earth, a thesis that he supported by the fact that pendulums with equal periods of time have different lengths at different latitudes. In his early dynamical papers, Newton attempted to explain planetary motion as a contest between gravity and centrifugal force, testifying as well to the influence of Descartes's suggestion that force is a real endeavor of bodies in circular motion. By 1679 Newton came to see orbital motion in terms of a force directed toward some center of motion that diverts bodies from their rectilinear paths, an approach that suggested that centrifugal force was a reaction to the centripetal force, according to Newton's third law of motion. Nevertheless, his early dynamical papers testify to the sway of Descartes's account of circular motion.

Not only did Descartes help to define the critical problem of dynamics, he also advanced a causal agency for its solution. All change is the result of the percussion of bodies. Descartes held that percussion, in addition to being perfectly intelligible, was the only way that one body could act on another in a closely packed cosmos. The third law of motion governs the exchange of motion during impact: "a body, upon coming in contact with a stronger one, loses none of its motion; but that, upon coming in contact with a weaker one, it loses as much as it transfers to that weaker body" (Descartes 1983, II.40, p. 61). The force of motion consists of two components. The velocity is one factor. The other is the size of the body, a concept that was too imprecise to be of much value in the formulation of a quantitative mechanics. Since God conserves the quantity of motion, one body can acquire motion only at the expense of another body, a suggestion that signified an important step toward the principle of the conservation of momentum and Newton's third law of motion (cf. Westfall 1971, p. 64). However, Descartes's third law of motion asserts nothing about the dynamical conditions under which exchanges of motion occur. Granted that impact takes place in a moment of time and the particles are perfectly hard and inelastic, there can be no physical interpretation of the process of impact and the transfer of motion. At impact, God redirects the motions of the bodies according to the secondary rule governing that particular case. The rule simply expresses what the result of God's adjustment will be, while on the physical plane the phenomenon is conceptually obscure. The seven, secondary rules of impact that Descartes advanced for particular cases, therefore, simply state the adjustment that God makes in order to conserve the quantity of motion (see Schuster 1977, pp. 690–91).

The third law of motion applies to perfectly hard bodies isolated from all others, a situation that can never be realized in Descartes's closely packed universe. For this reason, Descartes pointed out that his rules of impact would seem to conflict with experience (Descartes, 1983, II.43). Despite his knowledge of the correct rules for inelastic collision, Descartes persisted in retaining his rules of collision in the face of vocal criticism because correct rules for inelastic collision suggested that the quantity of motion in the cosmos would decrease with time. Moreover, the complete identification of rest and motion led Descartes to postulate a rest force, opposed and parallel to the moving force (quantity of motion) of a body in motion. It is from his conception that a body "which is at rest has some force to remain at rest, and consequently to resist everything which can change it" (Descartes 1983, II.43, p. 63) that Descartes deduced his puzzling fourth rule of impact, according to which a smaller body will never be able to put in motion a larger one, regardless of its speed, because it will not be able to overcome the force of resistance of the larger and stronger one (Descartes 1983, II.49, p. 66). Another factor is that Descartes regarded motion as a real state, or quality of bodies, that is to be conserved and that causes their being in the act of moving. His analysis of circular motion, for instance, rests on the view that the inertial tendency and the centrifugal tendency that it occasions are really in the body, in the sense that they are causes of the modal dispositions of bodies. What he failed to discern, however, was that his treatment of motion clashed with the relativity of motion, a principle that he embraced in name, though apparently not in substance. If the quantity of motion depends on the frame of reference, motion cannot be conserved in an absolute sense.

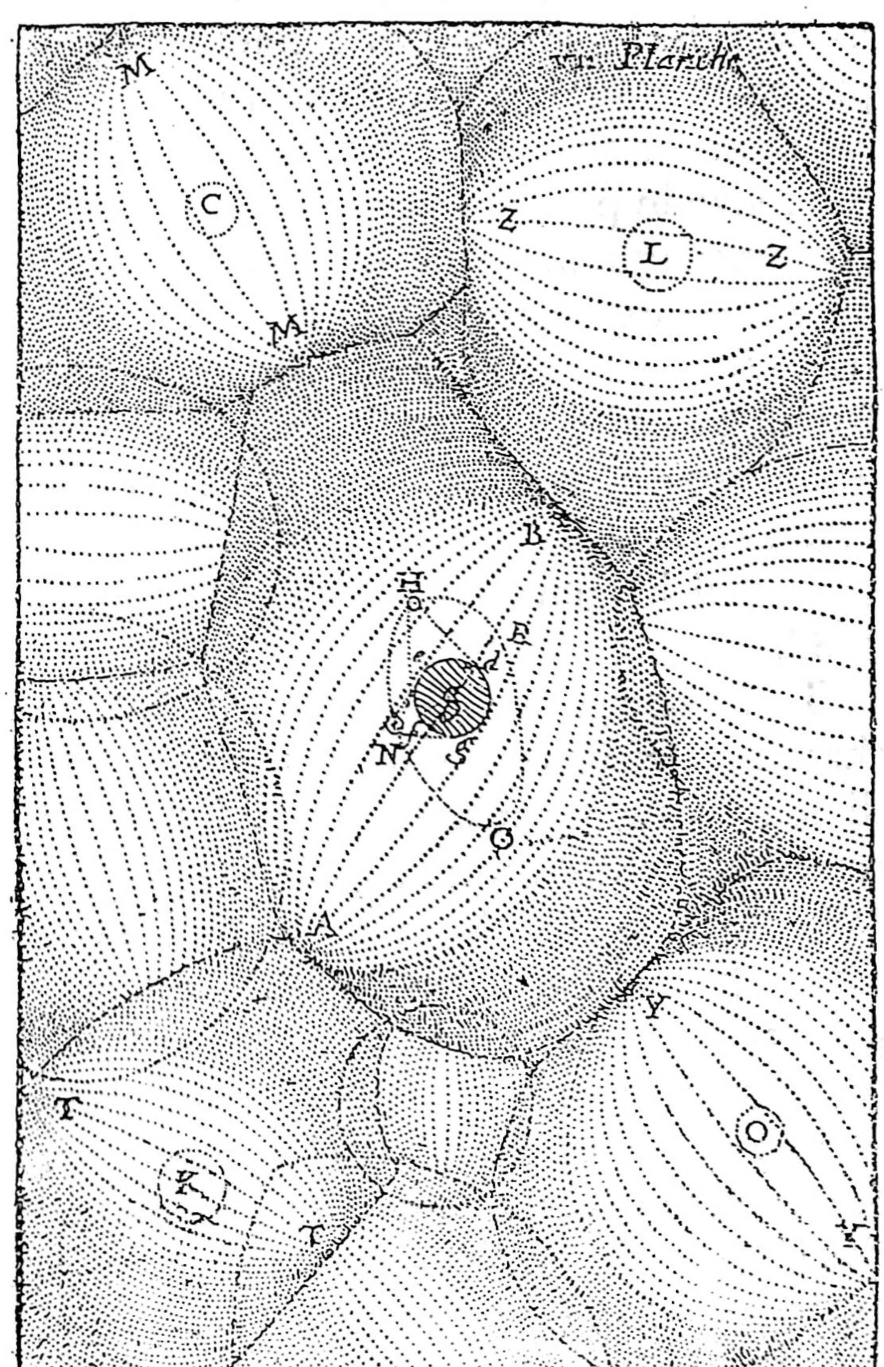
Whirlpools of Matter

Part III of the *Principles* presents Descartes's views on "the visible world." The cosmos is to be stripped of all forms, qualities, potencies, and entelechies and all obscure ideas whatsoever. Reason teaches us that matter is devoid of all secondary qualities and is to be conceived solely in terms of its solidity and continuous extension in three dimensions. Conceived simply as extension and its modifications, matter by its very nature is perfectly uniform and indefinitely divisible, thereby ruling out the existence of atoms in principle. Further, extension is held by Descartes to be an attribute that (along with its proper modes) cannot exist without a substance. Since extension is the essential attribute of corporeal nature, the idea of empty space, as distinct from extended matter, is rejected by Descartes as a fiction (see Descartes 1983, II.16–18). Indeed, to attribute the positive characteristics of extension to a vacuum that is said to be incorporeal is to ascribe properties to nonbeing. So strongly did Descartes hold to this view, that he dismissed Galileo's law of fall and of the pendulum on the grounds that they were fashioned in a vacuum.

Since God could have arranged nature in an infinity of ways (including some that we regard as logically impossible), our unaided reason is unable to fathom the composition of the world (i.e., the size, velocity, or motions of particles of matter). Descartes suggests that "we are now at liberty to assume anything we please, provided that everything we shall deduce from it is entirely in conformity with experience" (Descartes 1983, III.46). What we do know is that extended matter is divisible into countless parts. On this basis, Descartes conjectured that God originally divided matter into particles of uniform size and imparted two motions to each of them, one a rotation around their own centers, and a second propensity to rotate as a group around other centers equidistant from each other. On the face of it, this suggestion clashed with the account of creation in Genesis. Though he was anxious that the theology enjoined by his cosmology not incur the wrath of religious authority, Descartes reckoned that we will understand the visible world much better if we consider how it could have developed "from certain seeds" (Descartes 1983, III.45, p. 106). While accepting the biblical account of creation, Descartes believed that human understanding would be better served if we restated the genesis of the cosmos in purely mechanical terms.

In consequence of their circular movement, the particles of matter collide with one another, polishing and smoothing their corners through innumerable collisions. The original particles are thereby decomposed into two further elements of matter. The particles that are polished and smoothed by these collisions continue their circular motion, with a centrifugal tendency to recede from the center of rotation. They constitute the spherical boules of the second element. The first element consists of fine dust, the cosmic scrapings of the original particles. Material of the first element "is so tiny, and acquires such great speed, that the sole force of its motion can divide it into innumerable scrapings which . . . fill all the angles [spaces] into which the other parts of matter cannot enter" (Descartes 1983, III.49, p. 109). As the spherical particles recede, some of this highly agitated dust tends to accumulate in the center of each vortex, while the remainder fills the interstices between the particles of the second element, which envelops and revolves around the central accumulation of matter. In this way, the circular motion attributed to the original block of extended matter produces a whirlpool or a vortex of matter. Indeed, Descartes holds that innumerable vortices are created in this fashion. It is the presence of many such systems that ensures that the centrifugal tendency of the spherical boules does not translate into the actual radial movement of the spherical boules away from the center of rotation. Kepler is sometimes advanced as the inspiration for Descartes's vortex theory. This was the verdict of the German philosopher and mathematician, G.W. Leibniz, but the basic idea had been part of the Western intellectual tradition for more than 2,000 years. For example, in his *De caelo* (295.a:11–14), Aristotle pointed out that the belief in vortices was nurtured by the analogy with the whirlpool and the whirlwind.

A third element is produced from the original particles. As the cosmic scrapings produced by friction seek to pass through the interstices between the rapidly revolving spherical particles of the vortex, some are detained and become twisted and channeled in their passage. When they reach the edge of the body of the sun, they settle upon it in the way that scum produced by the boiling of liquids gathers on its surface. They form spots on the sun. Sometimes the scum is reabsorbed and forms an aether round the sun. Sometimes the solar scum increases until it extends over the entire surface area of the star, blocking it entirely from view. The expansive force of the star is thereby depleted, and in the course of time, it suffers encroachment from contiguous vortices. Eventually it is swept up by a neighboring vortex. If the velocity of the decaying star is greater than that of any part of the vortex that has swept it up, it will pass out of the range of that vortex and continue its movement from one vortex to another. Such a star is a comet. In the event that the encrusted star settles in a



Whirlpools of matter. In this illustration taken from Descartes's Principia philosophiae, *the sun* S *is situated in the midst of the vortex* AYBM, *pressed on all sides by contiguous vortices* C, K, O, *and* C.

portion of the revolving vortex that has a velocity equivalent to its own, it will continue to revolve in the vortex, wrapped in particles of the third element. Such an impoverished star is a planet. The several planets of our solar system are therefore vortices that have been swept up by the central sun-vortex. These same considerations are extended to the moon and other satellites. Once, these celestial bodies were vortices as well. They were swallowed up first by a planet and then by the sweep of the central sun.

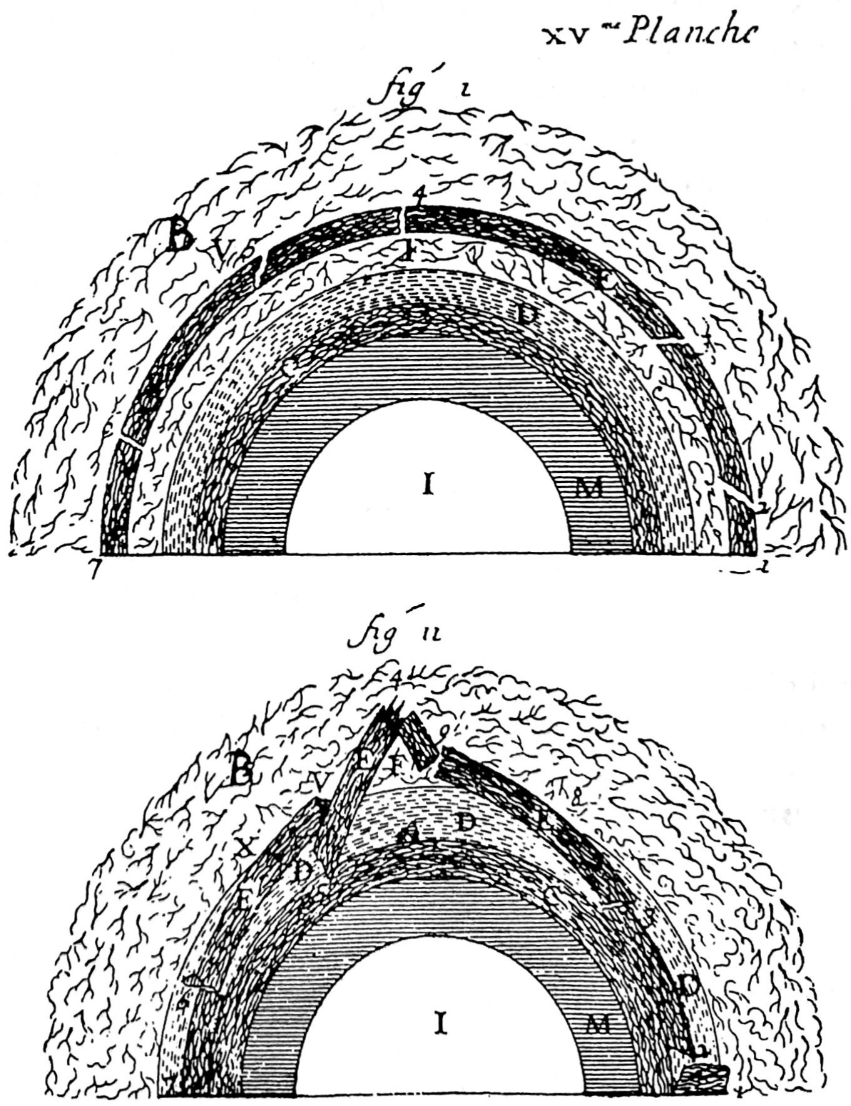
With this view, Descartes attempted to explain certain astronomical phenomena. The fact that the planets closer to the sun move faster than those farther away was explained by the hypothesis that the particles of the first element, rotating at the center of the vortical system, augment the speed of the layers close to the center. The fact that the linear speed of sunspots is slower than that of any planet was attributed to a solar atmosphere extending as far as Mercury (Descartes 1983, III.148). Descartes seems to have been unaware of Kepler's laws of planetary motion, but to furnish a mechanical explanation for the fact the planets do not move in perfect circles, he solicited the distortion caused by the unequal pressure of neighboring vortices (Descartes 1983, III.157). Descartes is often taken to task for failing to address Kepler's laws, unfairly it would appear, granted that no one prior to Newton regarded these laws as facts to be explained by physical theory (see Baigrie 1987).

To explain gravity, Descartes conjectured that the celestial matter that circulates in all directions about the earth tends to push all terrestial objects toward the earth (see Aiton 1972, pp. 55–58). By virtue of its greater speed, the celestial matter has more centrifugal force than earthly bodies have. If some terrestial body were to be released above the surface of the earth, it would therefore be displaced downward by the celestial matter rising to take its place. Only bodies containing the earthly matter of the third element are subject to gravitation. Of course, no bodies are composed solely of this matter; all bodies have pores that are filled with the ethereal elements. However, Descartes suggested that two bodies of the same bulk might contain larger or smaller pores and, therefore, different portions of the third element. In this event, their weights would be different. This view explained how two bodies of equal extension could have different weights; all bodies of a given volume contain the same bulk of matter, but only a fraction of this matter has any weight.

Descartes readily conceded his inability to prove that these elements exist. Even so, he defended his cosmology on account of its intelligibility: it involved considerations of the motions, size, shape, and arrangement of insensible particles, which were clear and distinct to the attentive mind. Additional support was furnished by the consistency between his postulated elements of matter and a theory of light as mechanical pressure. Descartes considered light as a tendency or as a pressure that crosses space instantaneously. Aristotle had outlined a similar view, but Descartes departed from received opinion by treating light in a material medium (see Sabra 1967, p. 46). According to Descartes's purely mechanical theory of light, the rotation of vortices gives rise to centrifugal forces which, in turn, drive streams of luminous globules outward from the sun and all luminous bodies in all directions. As a result, the intermediate layer of the atmosphere is compressed and it starts to tremble. What we experience as light is in fact the pressure exerted on the eye by these continuous streams of globules. Since each globule in a stream is in contact with the one immediately in front, any change of pressure at the center is felt at the extremity. It is this that occasions the impression that the velocity of light is infinite, when it is merely the tendency to motion that is communicated to the eye. Descartes's cosmology furnishes the three elements that are needed to motivate such an account. The sun and the stars produce light by mechanical agitation. The heavens of the second element propagate light. The earth, moon, planets, and comets of the third element reflect light and are opaque to it. The three elements, then, are hypothetical in the sense that they lack independent empirical support, but they are not arbitrary, as scholars often suppose, since they are designed to restate optical phenomena in purely mechanical terms (Descartes 1983, III.52).

The guiding assumptions of Descartes's cosmology were articulated and developed by such eminent scientists as Pierre Sylvain Régis, Christiaan Huygens, Jacques Rohault, Nicolas Malebranche, and Gottfried Leibniz and by the renowned family of Swiss mathematicians the Bernoullis. Clearly, they were held in thrall by the explanatory power of the general conception of the cosmos as a plenum, but it is important to note that Descartes's treatment of the mechanics of circular motion was equally attractive to scholars (e.g., Huygens, Leibniz, and Newton) who were interested in a rigorous solution to the mechanics of planetary motion. Moreover, we should not lose sight of the fact that Descartes's cosmological speculations were fruitful in domains other than mechanics. For instance, his account of the formation of the earth inspired Anathanasius Kircher's *Mundus subterraneus* (1664–65), the first modern work of geology.

Some of Descartes's central theses, such as his rules of impact and his account of the propagation of light, were known to be mistaken before Isaac Newton opposed the vortex theory with an account of forces acting on discrete bodies *in vacuo*. In his *Principia* (1687) Newton furnished an impressive battery of arguments that attacked Descartes's account of the circular motion of fluids. Since the inward parts of the vortex are always propagating their motion to the outward parts, Newton submitted that a vortex would eventually grind to a halt if some force unknown to Descartes were not added to it. Moreover, Newton contended that the mechanism of a vortex clashed with Kepler's third law of planetary motion, a challenge



The formation of the earth. The rigor with which Descartes developed his thesis that the heaven and earth are to be explained by the same set of principles is illustrated by his geological speculations. He suggests that the earth and the other planets were once stars, differing only in size. The changes in the earth's crust are explained by the gradual and continuous cooling of its central mass. In these illustrations, which are taken from the Principia philosophiae *(1644), the earth has a molten core* I, *surrounded by a sphere that is made of the same matter as sunspots* M, *a solid crust* C, *and a lighter crust that floats on an internal sea* D. *As pieces of the crust tilt, they become immersed in the sea and protrude as mountains, a thesis that enabled Descartes to explain the presence of tilted strata that do not follow the curved shape of the earth.*

that proponents of Descartes's views would be unable to surmount in the long run (see Newton 1934, p. 393). For the time being, however, these criticisms did little to dampen enthusiasm for Descartes's cosmology (see Baigrie 1988). Descartes's cosmology continued to attract adherents until 1740 or so, when the French mathematician and astronomer, Pierre Louis Moreau de Maupertuis, publicly declared his allegiance to the new science of Newton, primarily on account of the inability of Cartesian scientists to reconcile the mathematical relations implied by Kepler's laws of planetary motion with the mechanism of a vortex (see Baigrie 1987).

Experience

Regrettably, many scholars still embrace a distorted portrait of Descartes as an arch-rationalist who blatantly disregarded the evidence furnished by experience. While one may grant that Descartes was enamored of the intellect, his writings give no evidence that experience is to be dismissed out of hand. In his youthful *Regulae ad directionem ingenii* (1628), he complains of those philosophers "who take no account of experience and think that truth will spring from their brains like Minerva from the head of Jupiter" (Descartes 1984, vol. 1, p. 21). According to his biographer Baillet (1693), Descartes had a great passion for experiment. He conducted experiments on the weight of the air and on vibrating strings. He employed a device to study the motions of vapors. Descartes's anatomical studies of a wide variety of animals are well known and rightly praised for their attention to detail. Descartes's skill in designing and constructing new experimental devices and scientific instruments (such as the microscope and a compass for the construction of geometrical curves) is what we have grown to expect from science in action and not science in the imagination. Parts III and IV of the *Principles* constantly appeal to the evidence afforded by experiment and observation. The solution that Descartes advanced to the problem of the size of the rainbow in his *Les météores* is almost unknown, yet it displays the patient experiment and laborious calculation that we now readily associate with a healthy experimental outlook.

Descartes's cosmology was a critical factor in the transition from the finite and qualitative cosmos of the Middle Ages to the infinite cosmos described in mathematical detail by Newton. Even so, the suspicion lingers that his conception of the cosmos belongs entirely to the past (see Koyré 1965, ch. 1). To validate this suspicion, scholars often invoke the traditional portrait of Descartes as an armchair philosopher. If anything, Descartes's place in the history of science is secured by the philosophical clarity that he brought to the very idea of a mechanical cosmology, at a time when advances in the discrete mathematical sciences had taken science to the very threshold of a quantitative theory of the cosmos. Modern formulations of classical mechanics employ a cluster of concepts that are rightly viewed as descendants of concepts that found their first concrete application in Descartes's cosmology, a fact that testifies that the revolutionary developments of the seventeenth century were produced, at least in part, by clear thinking. However, if we seek to come to grips with Voltaire's verdict that, despite the fertility of his ideas, Descartes's cosmology was "un bon roman," the explanation is to be found not in the authority that Descartes conferred on reason per se but, ironically, in his refusal to place restrictions on the use of reason. Despite his great enthusiasm for experiment, Descartes's belief that the phenomena are merely the objective reality of clear and distinct mathematical ideas was ultimately responsible for this failure to produce stable, empirical results.

In Part III of the *Principles*, Descartes concedes that explanations of specific phenomena, such as magnetism, do not proceed deductively from first principles. He submits that to demonstrate that all natural phenomena can be explained according to the principles of the mechanical philosophy, the evidence afforded by experiment and observation is the only way of ruling out all but one of a number of alternative corpuscular arrangements for a given phenomenon; that is, appeals to experience, Descartes suggests, are our only prospect for closing down all but one deductive chain (see Garber 1978). This is a startling thesis, but invaluable as a clue to Descartes's attitude toward experience. While endorsing in name the device of an *experimentum crucis*, Descartes does not employ it in practice. Indeed, he almost never pursues dead ends, unlike Newton, for instance, who devotes an entire book of the *Principia* to isolating the dynamical conditions of Kepler's laws of planetary motion only to declare, in the third book of his masterful argument, that such conditions can never be realized in nature due to the universality of gravitational attraction.

Descartes relies on experience, not merely to furnish an independent tribunal for contending hypotheses but also to give empirical substance to his mechanical explanations. The corpuscular realm is concealed to sensation, even with the aid of sophisticated observational devices, such as the microscope of Descartes's own design which was distinguished by its employment of a hyperbolic lens. Though he held that sensation gives us a confused picture of the world, Descartes maintained that the phenomena conform to physical reality in one respect, namely, the mechanical properties of bodies; that is, natural phenomena are intrinsically mathematical in that they are the objective reality of clear and distinct mathematical ideas (Descartes 1983, II.4). On this basis, he reckoned that it was perfectly legitimate to infer the underlying properties and causes of natural phenomena by analogy with the mechanical properties of bodies that we experience. Even Descartes conceded that "in the analogies I use . . . I compare those things which because of their small size are not accessible to our senses with those which are, and which do not differ from the former more than a large circle differs from a small one" (1974, 6, pp. 367–8; cited by Clarke, p. 78). Although he envisioned his cosmological theses as moving deductively from first principles, properties identified at the macrolevel bear the burden of proof. In the *Discourse*, for example, he asserts that "the causes from which I deduce from them [effects] serve not so much to prove them as to explain them; indeed, quite to the contrary, it is the causes which are proved by the effects" (Descartes 1985, p. 150). Descartes's point seems to be that although his corpuscular explanations may be false, they are the best explanations for whatever mathematical clarity the phenomena seem to possess (see Descartes 1983, IV.205).

Although Descartes contended that his principles were mathematical, his explanations consist of a redescription of phenomena in the qualitative discourse of mechanics, which are then justified on account of their supposed intelligibility. What we encounter in Descartes's writings, therefore, is a subtle bias against detailed experimental work and in favor of simple experiments and observations about which many observers can be certain and in the interpretation of which there is less scope for differences of opinion (cf. Descartes 1985, p. 143; Adam and Tannery 1974, vol. 2, p. 542). His interest in the phenomena was restricted to that aspect that appeared, on the face of it, to be clear and distinct to the attentive mind; the rest of the world is passed over in silence. This methodological preference for simple observations and straightforward experiments imputes an exactness to the phenomena that they do not possess. Even Nicholas Malebranche, who was an earnest supporter of Cartesian science, conceded that "real levers and wheels are not the lines and circles of mathematics" (cited by Lenoble 1964, p. 193). It turns out that the phenomena are a great deal more perplexing than Descartes was prepared to recognize, and that experience never gives us an exact measure of the cosmos. Why the perception of mechanical properties only appears to give us a precise measure of the cosmos presented what was perhaps the single most significant obstacle to a quantitative theory of the cosmos, one that would only be surmounted by a cosmology that placed limits on the power of reason and developed experimental techniques for addressing the approximate and imprecise nature of phenomena.

See also ARISTOTLE'S COSMOLOGY; DESCARTES; NEWTONIAN COSMOLOGY

[B.S.B.]

Further Readings

Adam, C., and Tannery, P. (1974) Oeuvres de Descartes. Paris: Librairie Philosophique J. Vrin.

Aiton, E.J. (1972) The Vortex Theory of Planetary Motions. New York: Macdonald & Company.

Baigrie, B.S. (1987) Kepler's laws of planetary motion, before and after Newton's *Principia*: an essay on the transformation of scientific problems. Stud. Hist. Phil. Sci. *18*:177–208.

Baigrie, B.S. (1988) The vortex theory of planetary motion 1687–1713: empirical difficulties and guiding assumptions. In A. Donovan, L. Laudan, and R. Laudan (eds.): Scrutinizing Science. Dordrecht: D. Reidel Publishing Company, pp. 85–102.

Baillet, A. (1693) The Life of Monsieur Descartes. London: R. Simpson.

Blackwell, R.J. (1966) Descartes' laws of motion. Isis *57*:220–234.

Burke, J.G. (1966) Descartes' on the refraction and the velocity of light. Amer. J. Phy. *34*:1–32.

Chappell, V., and Doney, W. (1990) Twenty-Five Years of Descartes Scholarship 1960–1984. New York: Garland Publishing.

Clarke, D. (1982) Descartes' Philosophy of Science. Manchester: Manchester University Press.

Clarke, D. (1989) Occult Powers and Hypotheses: Cartesian Natural Philosophy Under Louis XIV. Oxford: Clarendon Press.

Crombie, A.C. (1970–80) Descartes. In C.C. Gillispie (ed.): The Dictionary of Scientific Biography.

Descartes, R. (1965) Discourse on Method, Optics, Geometry, and Meteorology. P.J. Olscamp (trans.). Indianapolis: Bobbs-Merrill Company, Inc.

Descartes, R. (1979) The World, or Treatise on Light. M. Mahoney (trans.). New York: Abaris Books.

Descartes, R. (1983) Principles of Philosophy. F.R. Miller and R.P. Miller (trans.). Dordrecht: Reidel Publishing.

Descartes, R. (1985) The Philosophical Writings of Descartes. J. Cottingham, R. Stoothoff, and D. Murdoch (trans.). Cambridge: Cambridge University Press.

Gabbey, A. (1971) Force and inertia in physics. Stud. Hist. Phil. Sci. 2:1–67.

Garber, D. (1978) Science and certainty in Descartes. In M. Hooker (ed.): Descartes: Critical and Interpretive Essays. Baltimore: Johns Hopkins University Press.

Gueroult, M. (1980) The metaphysics and physics of force in Descartes. In S. Gaukroger (ed.): Descartes, Philosophy, Mathematics and Physics. Sussex: The Harvester Press.

Gueroult, M. (1985) Descartes' Philosophy Interpreted According to the Order of Reasons. R. Ariew (trans.). Minneapolis: University of Minnesota Press.

Koyré, A. (1965) Newtonian Studies. Chicago: University of Chicago Press.

Lenoble, R. (1964) The seventeenth century scientific revolution. In R. Taton (ed.): The Beginnings of Modern Science. New York: Basic Books.

Meli, D.B. (1990) The relativization of centrifugal force. Isis *81*:23–43.

Milhaud, G. (1990) Descartes Savant. New York: Garland Publishing.

Newton, I. (1934) Sir Isaac Newton's Mathematical Principles of Natural Philosophy and His System of the World. F. Cajori (trans.). Berkeley: University of California Press.

Sabra, A.I. (1967) Theories of Light from Descartes to Newton. London: Oldbourne Book Company.

Schuster, J. (1977) Descartes and the Scientific Revolution, 1618–1634: An Interpretation. University Microfilms International.

Scott, J.F. (1990) The Scientific Work of René Descartes. New York: Garland Publishing.

Voltaire (1910) Letters to an English Nation. In C.W. Elliot (ed.): Harvard Classics, vol. 34. New York: P.F. Collier & Son.

Watson, R.A. (1987) The Breakdown of Cartesian Metaphysics. Atlantic Highlands: Humanities Press International.

Westfall, R.S. Force in Newton's Physics. New York: American Elsevier Publishing Company.

Digges, Thomas (1546–1595)

Trained in mathematics by his father, Leonard Digges, and by John Dee, Thomas Digges became the leading Copernican in England when in 1576 he added to his father's *Prognostication* a translation of parts of Copernicus's work. The influence of Digges's *Perfit Description of the Caelestiall Orbes* may, however, not have been great, especially beyond England. Digges was also a member of Parliament, involved with the repair of Dover harbor, and muster master general of the army in the Low Countries. A controversial historical study raises the possibility that Digges had a crude reflecting telescope and that observations with the in-