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4

The New Science: Kepler, Galileo, Mersenne

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Kepler's New Astronomy

Johannes Kepler (1571–1630) spent most of his life in Southern Germany, where he was born, and in nearby Austria. While training for the Lutheran ministry, he learned about the Copernican system from his mathematics professor at the University of Tubingen and became an enthusiastic convert. He never completed his religious training and spent his life as a teacher and mathematical consultant to governments.

Kepler's earliest theory, conceived when he was twenty-five years old, related the orbits of the planets to the five regular solids of classical geometry. The *Mysterium cosmographicum* (*The Cosmographical Mystery*, 1596), the treatise that advances this vision of nature as fundamentally mathematical, was the first avowedly Copernican work since the publication of *De revolutionibus Orbium Coelestium* (*On the Revolutions of the Heavenly Spheres*) in 1543. This book brought Kepler to the attention of Tycho Brahe (1546–1601), who in 1599 became mathematician for the emperor in Prague. When Brahe died in 1601, Kepler succeeded him, in the process inheriting Brahe's authoritative collection of astronomical observations, gathered over a twenty-five year period.

Not content with a geometrical description of the cosmos, Kepler was the first scientist to construct a physical theory to fit the new cosmos described by Copernicus. The guiding methodological principle of Kepler's new astronomy, advanced in his most important work, the *Astronomia nova* (*New Astronomy* 1609), is that astronomical problems are best resolved in terms of a mathematical analysis of their underlying physical causes. Kepler's brilliance is reflected in the way that he was able to extract a geometrically precise statement of the motions of the planets from the fairly crude conceptual resources at his disposal (bits and pieces of Aristotelian physics, Copernicus' astronomical theory, and Gilbert's study of the magnet, etc.) that were not tailored for the purposes of physical astronomy.

The central idea of Kepler's planetary theory is that the sun rotates on its own axis, carrying an image (*species immateriata*) of its body through the entire extent of the universe. This image was held by Kepler to have the power to overcome the resistance of the planet to motion (its inertia) and carry it in its grasp. As justification for this solar force, Kepler drew on Gilbert's *De Magnete* (*On the Magnet*, 1600). Just as the earth has the capacity to direct a magnetic needle north and south, Kepler held that the sun (which is a spherical body as well) directs the motion of the planet. For Kepler, the solar virtue is not a magnetic force as such. There is no true coition or coming together of the sun and the planet in the manner specified by Gilbert for two magnetic bodies and the sun is held, rather, to move the planet by the motion of its filaments. Kepler therefore conceived the solar virtue as a quasi-magnetic action that causes the planet to orbit the sun.

This suggestion implies that the planets have the same period of revolution, conforming to the sun's rotation on its axis. In order to reconcile the different periods of the planets with his magnetic theory, Kepler submitted that the planets are "inclined, because of matter, to remain in their place" (1969: 201). The introduction of the concept of inertia proved to be a remarkable event in the history of science, but Kepler supposed that the corporeality or inertia of matter occasions a resistance to motion on the part of the planets. A planet's velocity, rather, is determined by the strength of the solar force acting on the planet, relative to this resistance. More massive planets, Kepler contended, move more slowly on account of their greater inertia. In Book II of *De magnete*, Gilbert carefully distinguished the attraction due to the amber effect from the attraction caused by the lodestone. He discerned, for instance, that while all bodies may be made electrical, ferruginous substances alone can be made magnetical. For this reason, he proposed that separate disciplines be established to examine each kind of phenomenon. Moreover, in Book II, Chapter IV of his famous work, Gilbert recognized the effect of dull red heat on the magnetic virtue, namely, a magnet loses its power if it is placed in a hot fire until it becomes red-hot. Much later, in response to the suggestion of the Astronomer Royal, John Flamsteed (1646–1719), that the sun's magnetic power turns comets in a curved path, NEWTON (chapter 26) would object that the sun is "a vehemently hot body & magnetick bodies when made red hot lose their vertue" (Newton 1959–77, 2: 342). Newton was just reminding Flamsteed of a fact which seems to have been widely recognized. Setting aside the issue as to whether the force that drives the planets is central or rotational, Newton's point is that simple experiment reveals the error in classifying magnetic forces as gravitational ones. Gilbert had been careful to distinguish electric and magnetic forces, and it seemed clear to Newton that gravity constituted a third kind of attractive force. It is perhaps for this reason that Newton attributed vortical explanations of planetary motion to Kepler, and not the dynamical approach that he ascribed to Giovanni Borelli (1608–79), Robert Hooke (1635–1702), and himself (Newton 1934: 550).

The explanation for Kepler's conflation of magnetic attraction with gravitational attraction is complex but at least two points are pertinent. The first is the enchantment with circularity, which was his birthright as a Renaissance astronomer. The second is his goal of providing a physical basis for the Copernican theory. It appeared as though Gilbert's magnetic theory could be made to serve both ends, and Kepler clearly was less than rigorous in assessing its suitability for his new astronomy. The consequence of Kepler's enthusiasm for Gilbert's work is that the perfectly simple planetary path projected by the Copernican system emerges, in his planetary theory, as an idealized model of planetary motion under the sole influence of the circumsolar force.

Of course, the planet does not describe perfectly circular orbits, but its libratory approach to and from the sun proved to be a thorny problem. As an explanation, Kepler extended his magnetic hypothesis to the planet itself: "because there are present twofold threads…", by "the mingling of the planet's body and the sun's power" (1618–21: Kepler 1969, Book V, 209), the planet is compelled to describe an orbit oblique to the ecliptic. Furthermore, because the threads of latitude remain approximately parallel during the planet's revolution, it is gradually deflected after a number of revolutions. The plane contained by the orbit is only "approximately perfect" (i.e., circular) and so the center of the planetary globe does not return exactly to its starting point. The threads of libration compel the planet to draw away from the sun and return again, so that it describes an eccentric orbit, "not a perfect circle but one slightly narrower and more pressed in on the sides, like the figure of an ellipse" (Kepler 1969, p. 210).

There was still the critical problem of reconciling Kepler's geometrical hypotheses with the magnetic theory. During the course of his work, it became apparent that the planetary orbits were not circles, and that no number of epicycles could account for the irregularities of their paths. Although at first unable to characterize these paths accurately, Kepler recognized that the planets accelerate as they approach the sun, and slow down as they move away from it. In order to calculate the position of a planet at any time, he formulated two different laws. The first states that the velocity of a planet varies with its distance from the sun in such a way that a line joining the planet with the sun sweeps out equal areas in equal times; and the second says that the velocity of a planet varies inversely to the distance from the sun. The first is the form commonly known as Kepler's second law of planetary motion, while the second is known as the inverse-distance law. Although Kepler initially regarded these laws as equivalent, by the end of the *Astronomia nova* he had corrected the distance law and recognized its incompatibility with the area law. The implication of the area law was that the sun controls the motion of the planet.

The idea persists that Kepler's astronomical discoveries cleared away the cumbersome geometrical device of epicycles that had been the cornerstone of planetary astronomy since antiquity. There is no basis for this generalization. Kepler initially introduced the area law in the *Astronomia nova* as a convenient mathematical approximation to the inverse relation of distance and speed, but he came to see that the two rules are not equivalent. The area does not measure exactly the sum of the distances from the sun. The velocity of a planet is inversely proportional to its distance from the sun to a tangent line drawn through the planet, and not to its distance from the sun, as Kepler initially supposed (see Newton 1934: 63). The speed law can be employed in the regions of the apsides because the direct distance from the sun to a planet approximates the perpendicular distance from the sun to a line drawn through the planet's position, tangent to its orbit. While Kepler corrected his faulty distance law, and came to recognize the exactness of the area law, there is no evidence that he came to regard the area rule as more than a computational device.

It is when we turn to the matter of applying the ellipse cum area rule to practical astronomical problems that we confront the ramifications of Kepler's failure to relate the area rule to his physical theory. It is easy to forget that the ellipse hypothesis by itself has no observational consequences. One would suppose that in order to express the position of any planet as a function of time, all that is required is any two orbital positions separated by a given time. One could then compute the area swept out during this period and find another area swept out in the same time. But the motion of a planet on an ellipse is not uniform; even now, there is no closed mathematical expression for elliptical motion. The machinery of elliptic integrals overcomes this difficulty, but it was not a live option for the would-be Keplerian.

Kepler used the area law in his *Rudolphine Tables* (1627) to express orbital positions along an ellipse, but the calculations were fraught with difficulty. The ellipse hypothesis was rendered ineffectual as an astronomical tool unless it was combined with a technique for approximating orbital velocities. Even though he made no use of this principle, Kepler recognized that the empty focus of the ellipse provided a center of uniform rotation. This solution gained a fair amount of currency in the seventeenth century, but it had no basis in physical theory. Moreover, these techniques signified a return to the deeply embedded ideal of uniform rotation, and certainly not the brave new astronomy proclaimed by Kepler's *Astronomia nova*. Even if one embraced Kepler's ellipse hypothesis as a likely candidate for the orbital shape, in the absence of the theoretical and mathematical tools that would put the area rule on the scientific map, the end result would be an astronomy that departed only negligibly from the astronomy of Ptolemy and Copernicus.

These considerations help to explain why the area rule is absent in the scientific literature prior to Newton. Furthermore, since the area rule and the ellipse are tied together in Kepler's physical theory, there was no pressing reason for the astronomical community to treat Kepler's ellipse as more than a mere computational device. As competent an astronomer as Giovanni Cassini (1625–1712), the director of the renowned Paris Observatory, found that he could dispense with Kepler's ellipse hypothesis, and he actively sought alternatives for the modifications Kepler attempted to impose upon the Copernican system; for example, the ovals of Cassini. Cassini's proposal was in step with numerous astronomical treatises, which attempted to reduce the ellipse to epicyclic astronomy by constructing it as a curve traced out by an epicycle with a period of rotation equal to the period of revolution of its center along the deferent. Recognizing this fact allows us to explain why Kepler's impact on physical theory prior to 1687 was quite a bit less than one would expect.

The underlying problem stems from the fact that Kepler's celestial physics was conceived with a "perfect" geometrical figure in mind – a circle – that would result in the planet describing a Copernican orbit. Although in retrospect Kepler is heralded for his discovery of the elliptical orbit, the orbital shape is the result of the mitigating influence of the planetary body on the sun's solar image. The elliptical shape of the orbit emerges as a compromise between Kepler's Copernican solar theory and Tycho Brahe's data, and not as the consequence of a physical theory.

More than a decade later, in his *Harmonices mundi* (*Harmonics of the World*, 1619) Kepler formulated the third and most influential of his planetary laws, that the orbital periods of the planets have a definite relationship to their distance from the sun, expressed by the formula $P^2 = a^3$, where P is the planet's orbital period in years, and a is its distance from the sun in Astronomical Units (i.e., the distance from earth to the sun). With this third or harmonic law, the distance of any body in motion about the sun could be calculated by observing its orbital period.

Kepler's New Science of Vision

Though he is now celebrated for the laws of motion that have been immortalized in Isaac Newton's argument for universal gravitation, Kepler's laws of planetary motion were ignored by scientists for decades after his death. Even Galileo, did not appreciate the significance of Kepler's astronomical discoveries. In his lifetime, he was known for his optics, a field that he was introduced to during his tenure as assistant to Tycho Brahe. The great observational astronomer found in 1600 that the lunar diameter as formed by the rays in a camera obscura appeared smaller during a solar eclipse than at other times. Brahe's observation generated a curious intellectual puzzle that seemed to admit only two solutions: either the moon itself changed sizes or moved further away from the earth during the solar eclipse; or Brahe was somehow being deceived by the camera obscura.

This puzzle drew the attention of Kepler. The first solution presumed that the puzzle was astronomical in nature. Kepler rejected it out of hand. The puzzle, Kepler submitted in his *Ad Vitellionem paralipomena* (*Additions to Witelo*, 1604) involved the optics of the visual images (which he called *pictures*) formed behind the small apertures in the pinhole camera. The changing diameter of the moon was caused by the intersection of the optical mechanism with the rays of light. The deception detected by Brahe, Kepler reasoned, is built into the pinhole camera.

An unpalatable consequence of Kepler's hypothesis for received theories of knowledge was that naked-eye observation is somehow better off than instrument-mediated observation. This consequence was congenial to the Scholastic natural philosophy that dominated intellectual life in and around the universities. A central doctrine of Scholastic accounts of knowledge was that there is nothing in the mind that is not first in the senses. Equivocating the scientific with the sensible, these same scholars would soon oppose Galileo's startling telescopic observations with the common sense refrain that such things as Jupiter's moons and the craters of the moon are not available in ordinary sensation and so must be artifacts of Galileo's instrument.

Anticipating this objection, Kepler fatally undermined the Scholastic account of knowledge and the authority traditionally conferred on ordinary vision by pointing out that deception is also built into the human eye, which, he demonstrated to great effect, is an optical mechanism furnished with a lens that has focusing properties. Since the eye possesses an aperture, Kepler reasoned, it is liable to the same errors that attend the observation of eclipses with a camera obscura. Where Renaissance thinkers like della Porta were indifferent to the real or illusory status of what the camera obscura makes visible, Kepler was quite clear that the image is not seen in any literal sense but interpreted by the visual system.

According to Kepler's theory, the act of seeing involves the painting of an inverted picture on the retina, comparable to the picture that appears on the back of the camera obscura. It was Kepler who first drew a connection between seeing and picturing, and with it drew a line between picture and object (between nature and its representation) that was interlaced in Renaissance literature.

A startling consequence of Kepler's claim that our optical mechanism mediates the world is that the world must be seen differently through the eyes of other animals. Thanks to the Copernican system, natural philosophers were already furnished with a philosophical objection to the anthropocentrism of the received geocentric cosmology. With Kepler's pioneering work in vision science, the anti-anthropocentrism implicit in Copernicus' treatment of the earth as just another celestial body was now bolstered by science. As Kepler's views gathered momentum during the course of the seventeenth century, it is easy to see why natural philosophers (for example, Robert Hooke and his celebrated illustration of the eye of a grey drone fly) became consumed with studying the eyes of other animals and in reconstructing the world as pictured by their optical mechanisms.

Kepler himself was reluctant to speculate on what happens next after a picture is painted on the retina. Although he sketched a theory that owed a great deal to Medieval and Renaissance scholars, his considered judgment seems to have been that the associated psychological and epistemological problems start where the science of optics ends. Nevertheless, Kepler's work with the camera obscura stimulated the direction of philosophy in two ways: (a) the connection that he drew between seeing and picturing coalesced into a metaphor that described the relation of a perceiver and the position of a knowing subject to an external world; and (b) the analogy that he drew between the camera obscura and the human eye proved to be instrumental to the creation of the mechanical philosophy.

The Camera Obscura as metaphor

Renaissance scholars, such as Giovanni Battista della Porta (1538–1615), did not draw a distinction between the external world and its projection. By the mid seventeenth century, philosophers outside the mainstream scholastic tradition drew a firm distinction between image and object. (Scholars have identified many intellectual conduits whereby the guiding principles of scholastic philosophy continued to shape philosophical activity during the course of the seventeenth century. Here is one place where the current of medieval thought ran dry. Since this place is to be found in the scientific contributions of Kepler, it has largely been invisible to historians of philosophy who tend to steer clear of the history of the discrete mathematical sciences.) Kepler's claim that vision is a kind of picture-making raised a new set of epistemological and psychological problems, concerning the relationship between observer and external world, that resulted in the creation of a philosophical metaphor that profoundly influenced the direction of content of philosophical theory during the seventeenth century and beyond.

DESCARTES' (chapter 5) *La dioptrique* (1637) confirmed and added precision to Kepler's substantive optical claims, in particular, restating the analogy between the eye and the camera obscura. Descartes then turned to the associated epistemological issues raised by Kepler's metaphor, taking the view that picturing does not work by denotation, and so the pictures painted on the retina do not require the existence of external objects that resemble these pictures. These issues in the theory of representation have been revisited by contemporary philosophers and are well documented, but few scholars are aware that these issues exploded on the philosophical landscape as a consequence of Kepler's work with the camera obscura.

An interesting feature of metaphor, noted by Nelson Goodman (1976), is that as a metaphor takes root in an intellectual community, it comes to be seen as a literal truth. During the seventeenth century, attention shifted from attempts to account for picturing as such to assorted metaphysical worries about the status of claims about the external world given the fact that we do not have direct access to objects in perception.

At the same time, the camera obscura moved to the forefront as an epistemic model for representing the position of a knowing subject with respect to an external world. The famous passage from John Locke's *Essay Concerning Human Understanding* (2, 11, 17) asserts that "external and internal sensations are the windows by which light is let into this *dark room*; would the pictures coming into such a dark room but stay there and lie so orderly as to be found upon occasion it would very much resemble the understanding of man." The camera obscura, in this passage, is used to restructure the process of observation: the operation of the mind is completely separate from the apparatus that allows the formation of "pictures" or "resemblances." Locke professes that the manner by which impressions made on the retina by rays of light produce ideas in our minds is "incomprehensible," but this model was conducive to a juridical role to the observer within the camera obscura that allows the subject to guarantee and police the correspondence between exterior world and interior representation and to set aside anything disorderly. The camera obscura, then, as a model of perception was used by Locke to provide an answer to the problem raised by Kepler's claim that a picture is painted on the retina in vision – namely, skepticism with regard to the senses. This model was accepted by LEIBNIZ (chapter 18), but only with the caveat that the camera obscura is not a passive device but is endowed with an inherent capacity for structuring the ideas it receives.

Kepler and the Mechanical Philosophy

Kepler employed the camera obscura (a mechanical device) as a model for the human eye. His demonstration was the first concrete scientific realization of an analogy between things that exist in a pure state of nature and mechanical contrivances fashioned by hammer and tongs. Mechanical analogy, and the mechanical models that are generated by a process of analogous reasoning, is one of a handful of tools in the scientist's toolkit. The mechanization of the human eye proved to be the first in a long series of mechanical analogies that fill the pages of the sciences of the early modern period.

Kepler applied his mechanistic hypothesis to one particular organ (the eye), leaving its functioning in relation to the entire system of the body untouched. Descartes took the additional step, in a number of scientific treatises, of treating the entire living animal body as an inanimate machine. By focusing exclusively on the one question that had guided Kepler in his optical researches – what physical motions follow from each preceding motion – Descartes, HOBBES (chapter 22), and other natural philosophers created a methodological template for the mechanistic style of explanation that is so characteristic of modern science. Buoyed by Kepler's success, the principles that govern the movement of machines were extended by scientists to other organic and inorganic systems, and confidence in the veracity of explanations of phenomena in terms of the so-called mechanical properties of bodies took hold in the wider intellectual community. Mechanism, taken by philosophers as a guiding methodological assumption, came to be seen by rationalist and empiricist alike as a way of policing unruly and disorderly sensations.

Galileo and the Telescope

Born in Pisa, Italy in 1564, for the first twenty years of his adult life Galileo held chairs of mathematics at the University of Pisa and then at Padua. His research centered on mechanics and on an attempt to devise a mathematical language of bodies in motion, but the trajectory of his career changed quite suddenly with the invention of the telescope.

Although much ink has been spilled on this subject, nobody knows who first invented the telescope. An instrument that made distant objects appear both larger and nearer created a stir in the Netherlands in 1608. News of this amazing instrument reached Galileo in 1609. After confirming the existence of such an instrument, along with basic information on its construction, Galileo built his first refracting telescope in July of the same year. By the end of the year, he had succeeded in executing an instrument that represented objects 1,000 times larger and 30 times nearer than they appeared to the naked eye. The arrangement of lenses that Galileo employed consisted of an objective that is a converging, positive lens with a diverging, or negative, eye lens – an arrangement that is now restricted to opera and field glasses because the magnification is not great. The magnification that Galileo achieved with his instrument was the best that could be expected from such an arrangement of lenses.

Galileo turned this comparatively simple instrument to the skies in January of 1610. Astronomy was something of a departure for Galileo. He had little interest in this subject prior to 1604, when he had become interested in two astronomical questions: (a) if the Earth moved in space, as Copernicus contended, why was only one hemisphere of the sky visible? Moving away from the celestial sphere must bring one closer to one side, and so render more than half the sphere visible. Galileo was certain that this argument was groundless but he possessed no physical proof for the Copernican conjecture of a moving Earth. He wrote to Kepler to tell him that he believed in the soundness of the Copernican hypothesis, but Kepler was already one of the converted. And (b) if the heavens are immutable, as Aristotle had argued, why did a new star appear in 1604? Aristotelians demurred that the phenomenon was a meteorological one, occurring in the region below the surface of the moon, but Galileo and others were beginning to suspect that this and an earlier nova of 1572 lay beyond the sphere of the Moon, as Brahe had claimed many years earlier.

The telescope changed everything. Although the moon is unique among heavenly bodies in possessing features that are discernible to the naked eye, Galileo noticed small bright and dark spots changing in size as he watched that heretofore had been invisible. He concluded that the surface of the moon is endowed with what he thought were seas and "everywhere full of vast protuberances, deep chasms, and sinuosities," like the surface of the Earth. Noting that the summits of the highest elevations were illuminated at a considerable distance from the edge of the lunar crescent, with simple geometrical reasoning he concluded that the lunar mountains were at least four times higher than the mountains of the Earth.

Galileo then turned the telescope to the stars. Although the stars appeared brighter, they were not enlarged but looked even smaller through the telescope, unlike the planets, which gave the appearance of small disks. The only explanation was that the stars were situated at immense distances from the earth – farther than the planets. When he then trained the telescope on the constellation Orion, he discovered and recorded many stars, never before seen with the naked eye, in the belt and in the sword of the hunter. He then swung the telescope through The Milky Way, revealing that what was universally believed to be a luminous cloud in the sky was in fact a collection of individual stars.

His final set of observations proved to be the most dramatic. He observed tiny stars near Jupiter. On successive nights, he noticed that these four little stars stayed with Jupiter as it wandered through the fixed stars. He concluded that these must be moons circling Jupiter, and named them the Medicean stars, in honor of the Medici family that ruled Tuscany. Here was a Copernican system in miniature, which discredited the Aristotelian contention that there could only be one center of motion in the universe, the earth.

Galileo wasted little time and reported his observations in his *Sidereus nuncius* (*The Starry Messenger*), a small, heavily illustrated treatise that was published later that same year. This little book was a best-seller. When the initial run of 550 copies was sold out, a reissue appeared in Frankfurt within months. From his prison in the Castel dell' Ovo in Naples, Thomas Campanella wrote: "After your Message, O Galileo, all knowledge must be changed." Galileo became a celebrity overnight. It exercised such a withering influence upon the received cosmology of Aristotle and Ptolemy, with its geocentric planetary arrangement and sharp division of the cosmos into a perfect celestial realm and a corruptible terrestrial realm, that it deserves to be listed as one of the greatest books in the history of science.

In Prague, the Tuscan ambassador, Giulano di Medici, gave Kepler a copy with a request from Galileo for comments. Kepler's patron, the Emperor Rudoph II, soon made a similar request and Kepler quickly produced in the space of a few months a pamphlet called *A Discussion with the Starry Messenger*. This pamphlet extols Galileo's work, even though at the time Kepler had no telescope and had not even looked through one. Soon after, however, Kepler was afforded the opportunity to observe through one of Galileo's telescopes and thereupon published a second pamphlet. Kepler became so intrigued with the instrument that he temporarily broke off his own research to publish a book in 1611 on lenses and even to design an alternative telescopic arrangement featuring a biconvex lens combination that had many advantages over the Galilean arrangement.

For the first time, there was physical evidence that something was amiss in the Aristotelian universe. If Galileo's observations were sound, then quite evidently the many followers of Aristotle, who dominated intellectual life in and around the universities, would have to revise not just Aristotelian astronomy, but Aristotelian physics and with it, the entire edifice of Aristotelian philosophy.

The tragedy that descended on Galileo has been described in many places. Briefly, he was warned in 1616 by the Inquisition to cease teaching the Copernican theory, for it was now held "contrary to Holy Scripture." Copernicus' book itself was placed on the Index of Prohibited Books, and was suspended "until corrected." Galileo could not suppress what he believed to be the truth. Whereas Copernicus had invoked Aristotelian doctrine to make his theory plausible, Galileo urged acceptance of the heliocentric system on its own merits, apart from any such questions as those of faith and salvation. Although Galileo's battle with the church was officially waged over the Copernican system, the real issue, which was clear to Galileo from the beginning and to the theologians who were soon to stack the deck against him, was the right of the scientist to teach and defend his scientific beliefs.

In 1632, Galileo published the work *Dialogo Di Galileo Galilei* (*Dialogue Concerning the Two Chief World Systems*), advancing the case for Copernicus in a thinly disguised discussion of the relative strengths of the Ptolemaic and Copernican systems. Sale of the book was soon suspended. Galileo was ordered by the Pope to travel to Rome where he was confined for a few months, threatened with torture, and forced to make an elaborate formal renunciation of the Copernican theory. He was sentenced to perpetual confinement and forbidden to publish anything on Copernicanism. The trial reverberated through intellectual circles. Europe's most celebrated scientist had been forced to kneel in an act of public abjuration before the authority of the church.

Galileo's books continued to be printed and translated outside of Italy and exerted a lasting influence on scientific practice. He spent the next five years working on his new physics and composing his greatest book, the *Discorsi E Dimonstrazioni Matematiche, intorno a due nuoue scienze* (*Discourses on Two New Sciences*), which was published in 1638 in Leyden, out of the reach of censors and inquisitors. Fundamentally a work in dynamics, it presents his theory of projectiles, the resistance of solid bodies to concussion and fracture, the forces of cohesion in a body, the acceleration of motion, and the proof of the parabolic trajectory of ballistic missiles. Galileo died in 1642.

Galileo and the Creation of Mathematical Physics

Given the persuasive evidence that Galileo had marshaled for the Copernican theory, the question of the correct physics of a moving earth moved to center stage, not only for Galileo but also for those scientists who converted to the new astronomy after 1630 in ever increasing numbers. Galileo never worked out a satisfactory answer to this question. However, he carefully dismantled a number of standard objections to a moving earth, some of which were grounded in common sense and others of which were informed by the central tenets of Aristotelian science.

In a series of studies that covered the six-year period 1602–08, he found that, under ideal conditions, all bodies fall at the same rate, irrespective of differences of weight. This discovery delivered a decisive blow to Aristotelian physics, which held that the rate of fall is a function of weight (heavier bodies fall faster than light ones), and, by implication, that the earth must fall to the center of the planetary system. Equally important, he discovered that all falling bodies obey a mathematical law of uniform acceleration: the distances traversed in intervals of time by a body falling from rest with a uniformly accelerated motion are to each other as the squares of the time intervals. This discovery marked the introduction of time as an essential component of motion, without which its mathematical analysis could not proceed. Galileo then confirmed his mathematical analysis of the acceleration of falling objects with a series of experiments with an inclined plane that allowed him to measure the rate of acceleration of objects. Conducted under actual conditions, these celebrated experiments served to verify his mathematically derived results.

Galileo also showed that a projectile follows the path of a parabola and that its path is produced by the combination of two independent motions – a uniformly accelerated motion downward and a motion in a horizontal direction. The uniform horizontal motion is sometimes portrayed as an anticipation of the concept of inertia that was fully developed by Descartes and Isaac Newton, but the only perpetual motion that Galileo would allow was the circular motion of the planets around the sun. In his own way, Galileo was just as enamored with the circle as Kepler, and so perpetual motion in a circle was the only kind of inertia he could conceive. Kepler's elliptical orbits did not square with his conception of the cosmic order and they were rejected out of hand. Galileo's telescopic discoveries may have signaled his rejection of the Aristotelian distinction between celestial and terrestrial physics, but in physics he held fast to the distinction between motions that are natural (i.e., uniform and circular) and motions that are unnatural or violent (i.e., accelerated and rectilinear).

One of the key developments that is frequently identified with Galileo, but which in fact is repeated many times during the course of the seventeenth century, is the influence of what is often called a Platonic conception of nature. In his *Astronomia nova*, Kepler employed a tedious and ultimately fruitless method that involved plotting positions and drawing a line through them. He solved the problem of the planetary orbits, however, through the unexpected and sudden realization that the ellipse – a regular and familiar curve – satisfied all his needs. Although he had examined only a small portion of Mars' orbit, he immediately came to the conclusion that the orbit of Mars was an ellipse; indeed, that the planetary orbits were elliptical. This pattern is echoed in Galileo's discovery that the trajectory of a projectile was another familiar conic section, a parabola. As the seventeenth century unfolded, other relationships between physical quantities having simple mathematical forms were discovered in rapid succession – to name but a few, Snel's law, Boyle's law, Hooke's law, and Newton's law of universal gravitation. Boyle's law was deduced from empirical results. Others were not. All were buoyed by a confidence in the simplicity of nature which is reflected just as vividly in Galileo's willingness to believe that trajectories must be parabolical because nature works in geometrical ways as it is in his assigning physical properties, such as isochronism, to circular motion that he could not rigorously prove.

Another development that is properly identified with Galileo was his refinement of a method of problem solving that was inspired by his admiration of Archimedes. This method involved (a) the extraction of mathematically definite concepts from the variety of physical experience; and then (b) the experimental verification of general conclusions that are drawn from these concepts through a process of mathematical deduction. The principle on which Galileo's method was based was the conviction that once a determinate cause is established in physical theory, it is a fairly straightforward matter to tease out its physical consequences. The key involved defining these concepts with mathematical precision, and then following the chain of reasoning in a rigorous way. So long as there were no gaps or defects in the chain of mathematical reasoning, Galileo held that it was reasonable to regard the experimental verification as a proof of the determination of the cause. In what is perhaps the most celebrated passage in the annals of science, he wrote that

> Philosophy is written in this grand book the universe, which stands continually open to our gaze. But the book cannot be understood unless one first learns to comprehend the language and read the letter in which it is composed. It is written in the language of mathematics, and its characters are triangles, circles, and other geometric figures without which it is humanly impossible to understand a single word of it; without these one wanders about in a dark labyrinth. (Drake 1957: 237)

Galileo extended this method to the science of motion, thereby establishing the universal validity of such a science. Just as Galileo never mentioned the name of Archimedes without praise, later physicists (for example Isaac Newton) would come to see their own work as Galilean in conception. This method has now been extended over the whole of the physical sciences and has made inroads in to the life sciences as well.

Mersenne and the New Science

It seems reasonable to hold that early scientific societies arose as a natural response to the spontaneous desire among scientists for discussion and collaboration. It is true that this desire was a factor in the foundation of scientific societies but it was not the only (and perhaps not the most important) factor. By the 1630s, the medieval centralization of learning in Paris, Oxford, and Bologna had been weakened considerably. Scientists continued to flock to these centers, attracted not so much by the universities as by the quality of life of these centers and the chance of attracting a wealthy patron. Scientists needed money and encouragement. Believing that they could no longer look to the university and the church, they looked instead to a wealthy patron. In the spirit of an age when the support of a patron was vital to the flourishing of a program of research, Galileo purposely abandoned his university post at the University of Padua and took up a position as Philosopher and Mathematician at the ducal court of Tuscany (Florence). This theme of a scientist in search of a patron is repeated again and again during the first half of the seventeenth century, finally fading with the founding of the great national academies in London, Paris, Berlin, and St. Petersburg, with their royal patronage during the latter part of the century.

Another factor in the emergence of early scientific associations was the emergence of the Copernican doctrine as a lightning rod for scientists with often very different interests. It is true that Galileo was celebrated throughout Europe for his telescopic discoveries, but prior to 1630 his opinion carried little weight outside of a very small circle of pupils and friends who were already converts. If anything, Galileo's telescopic discoveries provoked a series of powerful counter-attacks against the new astronomy. Opponents of the new astronomy reasonably insisted that, while these new discoveries may have leveled the Ptolemaic system, they did not prove the truth of the Copernican system. This was the position taken by Tycho Brahe, who rejected both traditional and Copernican astronomy, and advanced a compromise of his own that was observationally equivalent to the Copernican system without the dubious physical hypothesis of a moving earth. This compromise was attractive to many astronomers, especially orthodox Catholic astronomers, such as Giambaptista Ricciolo (1598–1671), and the Jesuit Christopher Scheiner (1575–1650).

With the dismantling of the medieval centralization of learning, and the trial of Galileo in Italy, scientists began to rally around the Copernican hypothesis. There are no surviving records of early gatherings in Paris, chiefly because some of the more eminent scientists were rarely seen in the capital in the 1630s and 1640s. Descartes lived in Holland, Fermat in Toulouse, and PIERRE GASSENDI (chapter 6) was often at Aix-en-Provence. Although Paris was not the physical center of French science, it did serve as the intellectual center of scientific life thanks to the efforts of Marin Mersenne (1588–1648), a member of the Catholic order of monks known as the Minims.

In almost every respect, Mersenne moved with the intellectual currents of his time. He published an anti-Copernican treatise in 1623 and did not change his mind until 1630. Shortly thereafter, he accepted Galileo's ideas and the mechanical philosophy of Descartes. With Descartes, he believed that these phenomena were to be explained in purely mechanical terms as the effects of the motions of particles of matter. Concerning sound, he showed that the pitch of a note is proportional to the frequency of the sound wave that produces it. Musical intervals, such as octaves, are always fixed ratios of the frequency of sound waves.

Mersenne was not a gifted scientist. His interests were concentrated in the fields of music, acoustics and optics, fields with a mathematical flavor. Mersenne proposed in 1644 his Mersenne numbers, which are numbers generated from the formula $2^p - 1$, in which p is a prime number. Mersenne's formula did not represent all primes, but it contributed to developments in number theory. His emphasis was a reflection of his conviction, borrowed from St. Augustine, that God had created an orderly world based on mathematical ratios and proportions. Although direct knowledge of this world was limited to God, Mersenne held that the human mind can utilize mathematics – God's own language – to increase knowledge of the appearance of things. From the repeated and careful observations and measurement of natural phenomena, the scientist can extract patterns and regularities that will furnish the probable causes of those appearances.

Mersenne was a vigorous opponent of the radical skepticism that flourished in early seventeenth-century France. However, unlike Descartes who insisted on the possibility of morally certain knowledge, Mersenne found in a moderate form of skepticism a solution to the intellectual crisis that held literate and scientific culture in its grip. Aristotelians had always said that the knowledge furnished by the senses is trustworthy if the sense organs are not diseased and are functioning properly. If something looks red, it is safe to say that it is red, as a matter of fact. Paracelsians and Rosicrucians claimed that truth can be revealed to some individuals by divine inspiration, and Hermetists held that the revealed knowledge passed from Hermes Trismegistus represents privileged wisdom and is especially to be trusted. Mersenne agreed with the skeptics that we can never know the real truth of things, whether by way of the senses or through divine or Hermetic channels.

Mersenne's moderate skepticism was congenial to the view that the best that science can achieve is knowledge of appearances, and not of the essences of things. The causes of natural phenomena cannot be revealed by the study of their effects but, with careful observation and precise experimentation, nature can be understood well enough to guide human conduct: "it is enough, in order to have certain knowledge of something, to know its effects, its operations, and its use; we do not want to attribute to ourselves a greater science than that" (quoted in Dear 1988: 40). This view was most congenial to Mersenne's theism: science gives us a glimpse of how nature operates but does not explain why it works in the way that it does. This knowledge of the true nature of things was reserved for God alone.

Although his scientific legacy was meager, Mersenne was nevertheless a significant figure during the 1630s and 1640s. At a time when science was homeless, and the founding of the great national scientific societies still in the future, he orchestrated a vast network that linked some thirty or forty scientists and philosophers. His monastic cell at Place Royale served as a regular meeting place for what were in effect conferences of leading scientists and philosophers. His immense correspondence included virtually every French person who was active in the sciences, Galileo and others in Italy, and Hevelius at Dantzig, Thomas Hobbes and Theodore Haak in England, and many more. He enabled scholars who were often situated at enormous distances from one another to communicate more freely with one another and with the accumulated achievements of the past (through the young art of printing). He had an endless capacity for appreciating and reporting the work of others pretty accurately, and each correspondent benefited from Mersenne's shrewd insight into what was going forward in European science. He became involved in the publication of fundamental works, arranging for the publication of Thomas Hobbes' *De Cive*, gathering the objections to Descartes' *Meditations*, and translating Galileo's *Two Chief World Systems*.

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