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(*b.* Pisa, Italy, 15 February 1564; *d.* Arcetri, Italy, 8 January 1642)

physics, astronomy.

The name of Galileo is inextricably linked with the advent, early in the seventeenth century, of a marked change in the balance between speculative philosophy, mathematics, and experimental evidence in the study of natural phenomena. The period covered by his scientific publications began with the announcement of the first telescopic astronomical discoveries in 1610 and closed with the first systematic attempt to extend the mathematical treatment of physics from statics to kinematics and the strength of materials in 1638. The same period witnessed Kepler's mathematical transformation of planetary theory and Harvey's experimental attack on physiological dogma. Historians are divided in their assessment of this widespread scientific revolution with respect to its elements of continuity and innovation, both as to method and as to content. Of central importance to its understanding are the life and works of Galileo, whose personal conflict with religious authority dramatized the extent and profundity of the changing approach to nature.

Early Years. Galileo's father was Vincenzio Galilei, a musician and musical theorist and a descendant of a Florentine patrician family distinguished in medicine and public affairs. He was a member of the Florentine *Camerate,* a cultural group which included musicians whose devotion to the revival of Greek music and monody gave birth to opera. It was headed by giovanni Bardi, who sponsored Vincenzio's musical studies under Gioseffo Zarlino at Venice around 1561. In 1562 he married Giulia Ammannati of Pescia, with whom he settled at Pisa. Galileo was the eldest of seven children. His brother Michelangelo became a professional musician and spent most of his life abroad. Two of his sisters, Virginia and Livia, married and settled in Florence. Of the other children no record survives beyond that of their births.

Galileo was first tutored at Pisa by one Jacopo Borghini. Early in the 1570's, Vincenzio returned to Florence, where he resettled the family about 1575. Galileo was then sent to school at the celebrated monastery of Santa Maria at Vallombrosa. In 1578 he entered the order as a novice, against the wishes of his father, who removed him again to Florence and applied unsuccessfully for a scholarship on his behalf at the University of Pisa. Galileo resumed his studies with the Vallombrosan monks in Florence until 1581, when he was enrolled at the University of Pisa as a medical student.

The chair of mathematics appears to have been vacant during most of Galileo's years as a student at Pisa. His formal education in astronomy was thus probably confined to lectures on the Aristotelian *De Caelo* by the philosopher Francesco Buonamici. Physics was likewise taught by Aristotelian lectures, given by Buonamici and Girolamo Borro. As a medical student, Galileo may have received instruction from Andrea Cesalpino. His interest in medicine was not great; he was instead attracted to mathematics in 1583, receiving instruction from Ostilio Ricci outside the university. Ricci, a friend of Galileo's father and later a member of the Academy of Design at Florence, is said to have been a pupil of Niccolò Tartaglia. Galileo's studies of mathematics, opposed at first by his father, progressed rapidly; in 1585 he left the university without a degree and returned to Florence, where he pursued the study of Euclid and Archimedes privately.

From 1585 to 1589 Galileo gave private lessons in mathematics at Florence and private and public instruction at Siena. In 1586 he composed a short work, *La bilancetta*, in which he reconstructed the reasoning of Archimedes in the detection of the goldsmith's fraud in the matter of the crown of Hieron and described an improved hydrostatic balance. During the same period he became interested in problems of centers of gravity in solid bodies. During a visit to Rome in 1587, he made the acquaintance of the Jesuit mathematician Christoph Klau (Clavius). In 1588 he was invited by the Florentine Academy to lecture on the geography of Dante's *Inferno* treated mathematically. In the same year he applied for the chair of mathematics at the University of Bologna, seeking and obtaining from Guidobaldo del Monte an endorsement based on his theorems on the centers of gravity of paraboloids of revolution. The chair was awarded, however, to Giovanni Antonio Magini, probably on the basis of his superiority in astronomy, a subject in which Galileo appears to have shown little interest up to this time.

While Galileo was residing in Florence, his father was engaged in a controversy with Zarlino over musical theory. To destroy the old numerical theory of harmony, Vincenzio performed a series of experimental investigations of consonance and its relation to the lengths and tensions of musical strings. These he embodied in a published polemic of 1589, the *Discorso intorno all'opere di messer Gioseffo Zarlino da Chioggia*, and two unpublished treatises that survive among Galileo's papers. It is probable that Galileo's interest in the testing of mathematical rules by physical observations began with the musical experiments devised by his father during these years.

Professorship at Pisa. In 1589, on the recommendation of Guidobaldo, Galileo gained the chair of mathematics at the University of Pisa. The philosopher Jacopo Mazzoni, who came to Pisa at the same time, and Girolamo Mercuriale, professor of medicine, were close friends of the young mathematician. Luca Valerio, a Roman mathematician noted particularly for his later treatise on centers of gravity, met Galileo on a visit to Pisa and later corresponded with him. With other professors at Pisa, however, Galileo's relations were not so cordial, chiefly because of his campaign to discredit the prevailing Aristotelian physics to the advantage of his mathematical chair. His alleged demonstration at the Leaning Tower of Pisa that bodies of the same material but different weight fall with equal speed—if actually performed—was clearly not an experiment but a public challenge to the philosophers.

During Galileo's professorship at Pisa, he composed an untitled treatise on motion against the Aristotelian physics, now usually referred to as *De motu*. Its opening sections developed a theory of falling bodies derived from the buoyancy principle of Archimedes, an idea previously published by Giovanni Battista Benedetti in 1553–1554 and again in 1585. In the same treatise, Galileo derived the law governing equilibrium of weights on inclined planes and attempted to relate this law to speeds of descent. The result did not accord with experience—as Galilieo noted—which may be the principal reason for his having withheld the treatise from publication. The discrepancy arose from his neglect of acceleration, a phenomenon that he then considered to be evanescent in free fall and that he accounted for by a Hipparchian theory of residual impressed force. In order to reconcile that theory with fall from rest, Galileo introduced a conception of static forces closely allied to Newton's third law of motion. Equality of action and reaction, together with the idea of virtual velocities, pervades much of Galileo's physics. From his earliest demonstrations of equilibrium on inclined planes, Galileo limited the action of tendencies to motion to infinitesimal distances, unlike his ancient and medieval predecessors. In so doing, he was able to relate vertical fall to descent along circular arcs and tangential inclined planes, an achievement that was to provide him with the key to many phenomena after he recognized the essential role of acceleration.

In his *De motu*, Galileo undertook to destroy the Aristotelian dichotomy of all motions into natural and forced motions. He did this by introducing imaginary rotations of massive spheres. Rotations of homogeneous spheres, or of any sphere having its geometric center or its center of gravity at the center of the universe, he declared to be "neutral" motions, neither natural nor forced. Motions on the horizontal plane, or on imaginary spheres concentric with the earth's center, were likewise neutral—a conception that led Galileo to his restricted concept of inertia in terrestrial physics. His discussion of spheres in *De motu* shows further that in 1590 Galileo had not yet abandoned the geocentric astronomy, but suggests that he saw no difficulty in the earth's rotation as assumed in the semi-Tychonic astronomy.

Vincenzio Galilei died in 1591, leaving Galileo, as eldest son, with heavy domestic and financial responsibilities. Galileo's position at Pisa was poorly paid; he was out of favor with the faculty of philosophy and he had offended Giovanni de' Medici by criticizing a scheme for the dredging of the harbor of Leghorn. His disrespectful attitude toward the university administration is reflected in a jocular poem he composed against the wearing of academic robes. Thus, at the end of his three-year contract, Galileo had no hope of strengthening his position at Pisa and little promise even of reappointment. Once more with the aid of Guidobaldo, he moved to the chair of mathematics at Padua. The rival candidate was again Magini, whose hostility toward Galileo after this defeat became extreme.

Professorship at Padua. The atmosphere at Padua was propitious in every way to Galileo's development. He quickly made the acquaintance of free and erudite spirits, in such men as G. V. Pinelli and Paolo Sarpi. Among his students were Gianfrancesco Sagredo and Benedetto Castelli. A conservative professor, Cesare Cremonini, became his personal friend while staunchly opposing his anti-Aristotelian views. Padua was a gathering point of the best scholars in Italy and drew students from all over Europe. Under the Venetian government, the university enjoyed virtually complete freedom from outside interference.

Galileo lectured publicly on the prescribed topics: Euclid, Sacrobosco, Ptolemy, and the pseudo-Aristotelian *Questions of Mechanics*. Privately he gave instruction also on fortification, military engineering, mechanics, and possibly also on astronomy, although we lack concrete evidence of his having become deeply interested in that subject much before 1604. He composed several treatises for the use of his students. One, usually known as *Le mechaniche*, survives in three successive forms, dating probably from 1593, 1594, and about 1600. In this treatise, besides developing further his treatment of inclined planes, he utilized as a bridge between statics and dynamics the remark that an infinitesimal force would serve to disturb equilibrium. This move, although itself not unobjectionable, removed serious existing obstacles (which had been raised on logical grounds by Guidobaldo and Simon Stevin) from the mathematical analysis of dynamic problems. Galileo's treatise, before it was first published in a French translation by Marin Mersenne in 1634, circulated widely in manuscript, and an English manuscript translation was made in 1626. Its authorship was not always known to readers even in Italy, because Galileo's treatises composed for his students were invariably supplied in copies bearing no title or signature.

In May 1597 Galileo wrote to his former colleague at Pisa, Jacopo Mazzoni, defending the Copernican system against a mistaken criticism. In August of the same year he received copies of the *Mysterium cosmographicum*, the first book by Johannes Kepler, to whom he wrote expressing his sympathies with Copernicanism. Kepler replied, urging him to support Copernicus openly, but Galileo allowed this correspondence to languish. His preference for Copernicus at this time seems to have had a mechanical rather than an astronomical basis; he wrote to Kepler that it afforded an explanation of physical effects not given by its rivals. This referred to a tidal theory of Galileo's in which the double motion of the earth was invoked to account for the periodic disturbance of its water. The first notation concerning this theory occurs in the notebooks of Sarpi in 1595. Galileo wrote a treatise on it early in 1616, and wished to make it the central theme of his Copernican *Dialogue* of 1632, considering the tides to offer a compelling argument for the double motion of the earth.

It was also in 1597 that Galileo began the production—for sale—of a mathematical instrument, the sector or proportional compass. The idea for this instrument probably came to him from Guidobaldo, whose knowledge of it may in turn have been derived from Michel Coignet. Galileo transformed it from a simple device of limited use to an elaborate calculating instrument of varied uses and of great practical utility by adding to it a number of supplementary scales. He employed a skilled artisan to produce it (and other mathematical instruments) in his own workshop and wrote a treatise on its use for engineers and military men.

During his residence at Padua, Galileo took a Venetian mistress named Marina Gamba, by whom he had two daughters and a son. The elder daughter, Virginia, who was born in 1600, later became Galileo's chief solance in life. The vivacity of her mind and the sensitivity of her spirit—as well as her many impositions on her father's good nature—are evident in the letters that Galileo received and treasured. Both she and her sister Livia were entered in a nunnery near Florence at an early age, Virginia taking the name Maria Celeste. Livia, who took the name Arcangela, was of a peevish disposition and frail health. The son, Vincenzio, was later legitimized. After periods of estrangement from his father, Vincenzio became reconciled with him in his last years but did not long survive him. Marina Gamba remained at Venice when Galileo returned to Florence, and shortly afterward she married.

Early Work on Free Fall. Toward the end of 1602, Galileo wrote to Guidobaldo concerning the motions of pendulums and the descent of bodies along the arcs and chords of circles. His deep interest in phenomena of acceleration appears to date from this time. The correct law of falling bodies, but with a false assumption behind it, is embodied in a letter to Sarpi in 1604. Associated with the letter is a fragment, separately preserved, containing an attempted proof of the correct law from the false assumption. No clue is given as to the source of Galileo's knowledge of the law that the ratios of spaces traversed from rest in free fall are as those of the squares of the elapsed times. The law is algebraically derivable from the medieval mean-degree theorem known as the Merton rule, but Galileo's false assumption in 1604 contradicts the specific association of speed and time that is always found in medieval derivations of that theorem. Moreover, Galileo's faulty demonstration invoked no single instantaneous velocity as a mean or representative value; instead, it proceeded by comparison of *ratios* between infinite sets of instantaneously varying velocities. It is probable either that he observed a rough 1, 3, 5, . . . progression of spaces traversed along inclined planes in equal times and assumed this to be exact, or that he reasoned (as Christian Huygens later did) that only the oddnumber rule of spaces would preserve the ratios unchanged for arbitrary changes of the unit time. From this fact, the times-squared law follows immediately. Galileo's derivation of it from the correct definition of uniform acceleration followed only at a considerably later date.

The appearance of a supernova in 1604 led to disputes about the Aristotelian idea of the incorruptibility of the heavens, in which Galileo took an active part. He delivered three lectures to overflow crowds at Padua and prepared to publish an astronomical work; he did not do so, however, and only a short fragment of the manuscript survives. Lodovico delle Colombe, who published a theory of new stars at Florence, suspected Galileo of having written a pseudonymous attack on him, and it is certain that Galileo's ideas are reflected in still another pseudonymous work, published in rustic dialect at Padua in 1605, which ridiculed the professors of philosophy. In 1606, however, Galileo's attention was diverted from this dispute by the plagiarism of his proportional compass by Simon Mayr (or Marius, in the Latinized form used for publication), a German then at Padua, and Mayr's pupil Baldassar Capra. Galileo had privately printed a small edition of his treatise on the use of the compass in that year; Mayr and Capra produced a Latin book on the construction and use of the same instrument, claiming that Galileo had stolen it from them. Mayr had returned to Germany, so Galileo brought his action against Capra. The book was suppressed and Capra was expelled from the university. In the following year Galileo published a full account of the case in his first publicly circulated printed work, the *Difesa . . . contro alle calunnie & imposture di Baldessar Capra*.

Early in 1609, Galileo began the composition of a systematic treatise on motion in which his studies of inclined planes and of pendulums were to be integrated under the law of acceleration, known to him at least since 1604. In the composition of his treatise, he became aware that there was something wrong with his attempted derivation of 1604, which had assumed proportionality of speed to space traversed. Accordingly, he introduced in its place two propositions drawn from mechanics, which he submitted for criticism to Valerio. Galileo received Valerio's reply in July 1609, just after his attention had again been diverted from mechanics, this time by news of the invention of the telescope.

The Telescope. A Dutch lens-grinder, Hans Lipperhey, had applied in October 1608 to Count Maurice of Nassau for a patent on a device to make distant objects appear closer. Sarpi, whose extensive correspondence (maintained for theological and political reasons) kept him currently informed, learned of this device within a month. Somewhat skeptical, he applied for further information to Jacques Badovere (Giacomo Badoer), a former pupil of Galileo's then at Paris. In due course the report was confirmed. Galileo heard discussions of the news during a visit to Venice in July 1609, learned from Sarpi that the device was real, and probably heard of the simultaneous arrival at Padua of a foreigner who had brought one to Italy. He hastened back to Padua, found that the foreigner had left for Venice, and at once attempted to construct such a device himself. In this he quickly succeeded, sent word of it to Sarpi, and applied himself to the improvement of the instrument. Sarpi, who had meanwhile been selected by the Venetian government to assess the value of the device offered for sale to them by the stranger, discouraged its purchase. Late in August, Galileo arrived at Venice with a nine-power telescope, three times as effective as the other. The practical value of this instrument to a maritime power obtained for him a life time appointment to the university, with an unprecedented salary for the chair of mathematics. The official document he received, however, did not conform to his understanding of the terms he had accepted. As a result, he pressed his application for a post at the Tuscan court, begun a year or two earlier.

Galileo's swift improvement of the telescope continued until, at the end of 1609, he had one of about thirty power. This was the practicable limit for a telescope of the Galilean type, with plano-convex objective and plano-concave eyepiece. He turned this new instrument to the skies early in January 1610, with startling results. Not only was the moon revealed to be mountainous and the Milky Way to be a congeries of separate stars, contrary to Aristotelian principles, but a host of new fixed stars and four satellites of Jupiter were promptly discovered. Working with great haste but impressive accuracy, Galileo recited these discoveries in the *Sidereus nuncius*, published at Venice early in March 1610.

His sudden fame assisted Galileo in his negotiations at Florence. Moreover, the new discoveries made him reluctant to continue teaching the old astronomy. In the summer of 1610, he resigned the chair at Padua and returned to Florence as mathematician and philosopher to the grand duke of Tuscany, and chief mathematician of the University of Pisa, without obligation to teach.

Galileo's book created excitement throughout Europe and a second edition was published in the same year at Frankfurt. Kepler endorsed it in two small books, the *Dissertatio cum Nuncio Sidereo*, published before he had personally observed the new phenomena, and the *Narratio de observatis a se quatuor Jovis satellitibus*, published a few months later. Other writers attacked the claimed discoveries as a fraud. Galileo did not enter the controversy but applied himself to further observations. He discovered, later in 1610, the oval appearance of Saturn and the phases of Venus. His telescope was inadequate to resolve Saturn's rings, which he took to be satellites very close to the planet. The phases of Venus removed a serious objection to the Copernican system, and he saw in the satellites of Jupiter a miniature planetary system in which, as in the Copernican astronomy, it could no longer be held that all moving heavenly bodies revolved exclusively about the earth.

Early in 1611 Galileo journeyed to Rome to exhibit his telescopic discoveries. The Jesuits of the Roman College, who had at first been dubious, confirmed them and honored Galileo. Federico Cesi feted Galileo and made him a member of the Lincean Academy, the first truly scientific academy, founded in 1603. The pope and several cardinals also showed their esteem for Galileo.

Controversies at Florence. Shortly after his return to Florence, Galileo became involved in a controversy over floating bodies. In that controversy an important role was played by Colombe, who became the leader of a group of dissident professors and intriguing courtiers that resented Galileo's position at court. Maffeo Barberini—then a cardinal but later to become pope—took Galileo's side in the dispute. Turning again to physics, Galileo composed and published a book on the behavior of bodies placed in water (*Discorso . . . intorno alle cose che stanno ub su l'acqua, o in quella si muovono)*, in support of Archimedes and against Aristotle, of which two editions appeared in 1612. Using the concept of moment and the principle of virtual velocities, Galileo extended the scope of the Archimedean work beyond purely hydrostatic considerations.

While this work was in progress, Galileo received from Marcus Welser of Augsburg a short treatise on sunspots that Welser had published pseudonymously for the Jesuit Christoph Scheiner, asking Galileo's opinion of it. Galileo replied in three long letters during 1612, demolishing Scheiner's conjecture that the spots were tiny planets. He asserted also that he had observed sunspots much earlier and had shown them to others at Rome early in 1611. This set the stage for deep enmity of Scheiner toward Galileo, which, however, did not take active form at once.

Galieo's *Letters on Sunspots* was published at Rome in 1613 under the auspices of the Lincean Academy. In this book Galileo spoke out decisively for the Copernican system for the first time in print. In the same book he found a place for his first published mention of the concept of conservation of angular momentum and an associated inertial concept. During its composition he had taken pains to determine the theological status of the idea of incorruptibility of the heavens, finding that this was regarded by churchmen as an Aristotelian rather than a Catholic dogma. But attacks against Galileo and his followers soon appeared in ecclesiastical quarters. These came to a head with a denunciation from the pulpit in Florence late in 1614.

In December 1613 it had happened that theological objections to Copernicanism were raised, in Galileo's absence, at a court dinner, where Galileo's part was upheld by Benedetto Castelli. Learning of this, Galileo wrote a long letter to Castelli concerning the inadmissibility of theological interference in purely scientific questions. After the public denunciation in 1614, Castelli showed this letter to an influential Dominican priest, who made a copy of it and sent it to the Roman Inquisition for investigation. Galileo then promptly sent an authoritative text of the letter to Rome and began its expansion into the *Letter to Christina*, composed in 1615 and eventually published in 1636. Galileo argued that neither the Bible nor nature could speak falsely and that the investigation of nature was the province of the scientist, while the reconciliation of scientific facts with the language of the Bible was that of the theologian.

The book on bodies in water drew attacks from four Aristotelian professors at Florence and Pisa, while a book strongly supporting Galileo's position appeared at Rome. Galileo prepared answers to his critics, which he turned over to Castelli for publication in order to avoid personal involvement. Detailed replies to two of them (Colombe and Grazia), written principally by Galileo himself, appeared anonymously in 1615, with a prefatory note by Castelli implying that he was the author and that Galileo would have been more severe.

Late in 1615 Galileo went to Rome (against the advice of his friends and the Tuscan ambassador) to clear his own name and to prevent, if possible, the official suppression of the teaching of Copernicanism. In the first, he succeeded; no disciplinary action against him was taken on the basis of his letter to Castelli or his Copernican declaration in the book on sunspots. In the second objective, however, he failed. Pope Paul V, irritated by the agitation of questions of biblical interpretation— then a bone of contention with the Protestants—appointed a commission to determine the theological status of the earth's motion. The determination was adverse, and Galileo was instructed on 26 February 1616 to abandon the holding or defending of that view. No action was taken against him, nor were any of his books suspended. A book by the theologian Paolo Antonio Foscarini reconciling the earth's motion with the Bible was condemned, and the work of Copernicus and a commentary on Job by Diego de Zuñiga were suspended pending the correction of a few passages. One contemporary document, bound into the proceedings but of uncertain reliability, states that Galileo was also ordered never to discuss the forbidden doctrine again. If such an order was given, it was in contravention of certain specific instructions of the pope and had no legal force.

Returning to Florence, Galileo took up a practical and noncontroversial problem, the determination of longitudes at sea. He believed that this could be solved by the preparation of accurate tables of the eclipses of the satellites of Jupiter, which were of frequent occurrence and could be observed telescopically from any point on the earth. As a practical matter, the eclipses could neither be predicted with sufficient accuracy nor observed at sea with sufficient convenience to make the method useful.

It is probable that Galileo also returned during this period to his mechanical investigations, interrupted in 1609 by the advent of the telescope. A Latin treatise by Galileo, *De motu accelerato*, which correctly defines uniform acceleration and much resembles the definitive text reproduced in his final book, seems to date from this intermediate period, and copies of many of his propositions in kinematics exist in the handwriting of Mario Guiducci, who studied under Galileo at this time.

In 1618 three comets attracted the attention of Europe and became the subject of many pamphlets and books. One such book was printed anonymously by Orazio Grassi, the mathematician of the Jesuit Roman College. Galileo was bedridden at the time, but he discussed his views on comets with Guiducci, who then delivered lectures on them to the Florentine Academy and published them over his own name. In these lectures, which were largely dictated or corrected by Galileo, the anonymous Jesuit was subjected to criticism. The result was a direct attack on Galileo by Grassi, under the pseudonym of Lotario Sarsi, published in 1619.

Galileo replied, after much delay, with one of the most celebrated polemics in science, *Il saggiatore* (*the Assayer*). It was addressed to Virginio Cesarini, a young man who had heard Galileo debate at Rome in 1615–1616 and had written to him in 1619 to extol the method by which Galileo had opened to him a new road to truth. Since he could no longer defend Copernicus, Galileo avoided the question of the earth's motion; instead, he set forth a general scientific approach to the investigation of celestial phenomena. He gave no positive theory of comets, but developed the thesis that arguments from parallax could not be decisive concerning their location until it was first demonstrated that they were concrete moving objects rather than mere optical effects of solar reflection in seas of vapor. No such proof appeared to him to be available. In the course of his argument, Galileo distinguished physical properties of objects from their sensory effects, repudiated authority in any matter that was subject to direct investigation, and remarked that the book of nature, being written in mathematical characters, could be deciphered only by those who knew mathematics.

The *Saggiatore* was printed in 1623 under the auspices of the Lincean Academy. Just before it emerged from the press, Maffeo Barberini became pope as Urban VIII. The academicians dedicated the book to him at the last minute. Cesarini was appointed chamberlain by the new pope, who had long been Galileo's friend and was a patron of science and letters. Galileo journeyed to Rome in 1624 to pay his respects to Urban, and secured from him permission to discuss the Copernican system in a book, provided that the arguments for the Ptolemaic view were given an equal and impartial discussion. Urban refused to rescind the edict of 1616, although he remarked that had it been up to him, the edict would not have been adopted.

Dialogue on the World Systems. The *Dialogue Concerning the Two Chief World Systems* occupied Galileo for the next six years. It has the literary form of a discussion between a spokesman for Copernicus, one for Ptolemy and Aristotle, and an educated layman for whose support the other two strive. Galileo thus remains technically uncommitted except in a preface which ostensibly supports the anti-Copernican edict of 1616. The book will prove, he says, that the edict did not reflect any ignorance in Italy of the strength of pro-Copernican arguments. The contrary is the case; Galileo will add Copernican arguments of his own invention, and thus he will show that not ignorance of or antagonism to science, but concern for spiritual welfare alone, guided the Church in its decision.

The opening section of the *Dialogue* critically examines the Aristotelian cosmology. Only those things in it are rejected that would conflict with the motion of the earth and stability of the sun or that would sharply distinguish celestial from terrestrial material and motions. Thus the idea that the universe has a center, or that the earth is located in such a center, is rejected, as is the idea that the motion of heavy bodies is directed to the center of the universe rather than to that of the earth. On the other hand, the Aristotelian concept of celestial motions as naturally circular is not rejected; instead, Galileo argues that natural circular motions apply equally to terrestrial and celestial objects. This position appears to conflict with statements in later sections of the book concerning terrestrial physics. But uniform motion in precise circular orbits also conflicts with actual observations of planetary motions, whatever center is chosen for all orbits. Actual planetary motions had not been made literally homocentric by any influential astronomer since the time of Aristotle. Galileo is no exception; in a later section he remarked on the irregularities that still remained to be explained. Opinion today is divided; some hold that the opening arguments of the *Dialogue* should be taken as representative of Galileo's deepest physical and philosophical convictions, while others view them as mere stratagems to reduce orthodox Aristotelian opposition to the earth's motion.

Important in the *Dialogue* are the concepts of relativity of motion and conservation of motion, both angular and inertial, introduced to reconcile terrestrial physics with large motions of the earth, in answer to the standard arguments of Ptolemy and those added by Tycho Brahe. The law of falling bodies and the composition of motions are likewise utilized. Corrections concerning the visual sizes and the probable distances and positions of fixed stars are discussed. A program for the detection of parallactic displacements among fixed stars is outlined, and the phases of Venus are adduced to account for the failure of that planet to exhibit great differences in size to the naked eye at perigee and apogee. Kepler's modification of the circular Copernican orbits is not mentioned; indeed, the Copernican system is presented as more regular and simpler than Copernicus himself had made it. Technical astronomy is discussed with respect only to observational problems, not to planetary theory.

To the refutation of conventional physical objections against terrestrial motion, Galileo added two arguments in its favor. One concerned the annual variations in the paths of sunspots, which could not be dynamically reconciled with an absolutely stationary earth. Geometrically, all rotations and revolutions could be assigned to the sun, but their conservation would require very complicated forces. The Copernican distribution of one rotation to the sun and one rotation and one revolution to the earth fitted a very simple dynamics. The second new argument concerned the existence of ocean tides, which Galileo declared, quite correctly, to be incapable of any physical explanation without a motion of the earth. His own explanation happened to be incorrect; he argued that the earth's double motion of rotation and revolution caused a daily maximum and minimum velocity, and a continual change of speed, at every point on the earth. The continual variation of speed of sea basins imparted different speeds to their contained waters. The water, free to move within the basins, underwent periodic disturbances of level, greatest at their coasts; the period depended on sizes of basins, their east-west orientations, depths, and extraneous factors such as prevailing winds. In order to account for monthly and annual variations in the tides, Galileo invoked an uneven speed of the earthmoon system through the ecliptic during each month, caused by the moon's motion with respect to the earth-sun vector; for annual seasonal effects, he noted changes of the composition of rotational and revolutional components in the basic disturbing cause.

The *Dialogue* was completed early in 1630. Galileo took it to Rome, where it was intended to be published by the Lincean Academy. There he sought to secure a license for its printing. This was not immediately granted, and he returned to Florence without it. While the matter was still pending, Federico Cesi died, depriving the Academy of both effective leadership and funds. Castelli wrote to Galileo, intimating that for other reasons he would never get the Roman imprimatur and advising him to print the book at Florence without delay. Negotiations ensued for permission to print the book at Florence. Ultimately these were successful, and the *Dialogue* appeared at Florence in March 1632. A few copies were sent to Rome, and for a time no disturbance ensued. Then, quite suddenly, the printer was ordered to halt further sales, and Galileo was instructed to come to Rome and present himself to the Inquisition during the month of October.

The Trial of Galileo. The background of the action is fairly clear. Several ecclesiastical factions were hostile to the book but at first produced only shallow pretexts to suppress it. More serious charges were lodged against Galileo when Urban was persuaded that his own decisive argument against the literal truth of the earth's motion—that God could produce any effect desired by any means—had been put in the mouth of the simpleminded Aristotelian in the dialogue as a deliberate personal taunt by Galileo. Next, a search of the Inquisition files of 1616 disclosed the questionable document previously mentioned, which contained a specific threat of imprisonment for Galileo if he ever again discussed the Copernican doctrine in any way. Urban, having known nothing of any personal injunction at the time Galileo sought his permission to write the book, assumed that Galileo had deceitfully concealed it from him. The case was thereafter prosecuted with vindictive hostility. Galileo, who had either never received a personal injunction or had been told that it was without force, was unaware of any wrongdoing in this respect.

Confined to bed by serious illness, he at first refused to go to Rome. The grand duke and his Roman ambassador intervened stoutly in his behalf, but the pope was adamant. Despite medical certificates that travel in the winter might be fatal, Galileo was threatened with forcible removal in chains unless he capitulated. The grand duke, feeling that no more could be done, provided a litter for the journey, and Galileo was taken to Rome in February 1633.

The outcome of the trial, which began in April, was inevitable. Although Galileo was able to produce an affidavit of Cardinal Bellarmine to the effect that he had been instructed only according to the general edict that governed all Catholics, he was persuaded in an extrajudicial procedure to acknowledge that in the *Dialogue* he had gone too far in his arguments for Copernicus. On the basis of that admission, his *Dialogue* was put on the Index, and Galileo was sentenced to life imprisonment after abjuring the Copernican “heresy.” The terms of imprisonment were immediately commuted to permanent house arrest under surveillance. He was at first sent to Siena, under the charge of its archbishop, Ascanio Piccolomini. Piccolomini, who is said to have been Galileo’s former pupil, was very friendly to him. Within a few weeks he had revived Galileo’s spirits—so crushed by the sentence that his life had been feared for—and induced him to take up once more his old work in mechanics and bring it to a conclusion. While at Siena, Galileo began the task of putting his lifelong achievements in physics into dialogue form, using the same interlocutors as in the *Dialogue*.

Piccolomini’s treatment of Galileo as an honored guest, rather than as a prisoner of the Inquisition, was duly reported to Rome. To avoid further scandal, Galileo was transferred early in 1634 to his villa at Arcetri, in the hills above Florence. It was probably on the occasion of his departure from Siena that he uttered the celebrated phrase “Eppur si muove,” apocryphally said to have been muttered as he rose to his feet after abjuring on his knees before the Cardinals Inquisitors in Rome. The celebrated phrase, long considered legendary, was ultimately discovered on a fanciful portrait of Galileo in prison, executed about 1640 by Murillo or one of his pupils at Madrid, where the archbishop’s brother was stationed as a military officer.

Galileo was particularly anxious to return to Florence to be near his elder daughter. But she died shortly after his return, in April 1634, following a brief illness. For a time, Galileo lost all interest in his work and in life itself. But the unfinished work on motion again absorbed his attention, and within a year it was virtually finished. Now another problem faced him: the printing of any of his books, old or new, had been forbidden by the Congregation of the Index. A manuscript copy was nevertheless smuggled out to France, and the Elzevirs at Leiden undertook to print it. By the time it was issued, in 1638, Galileo had become completely blind.

Two New Sciences. The title of his final work, *Discourses and Mathematical Demonstrations Concerning Two New Sciences* (generally known in English by the last three words), hardly conveys a clear idea of its organization and contents. The two sciences with which the book principally deals are the engineering science of strength of materials and the mathematical science of kinematics. The first, as Galileo presents it, is founded on the law of the lever; breaking strength is treated as a branch of statics. The second has its basis in the assumption of uniformity and simplicity in nature, complemented by certain dynamic assumptions. Galileo is clearly uncomfortable about the necessity of borrowing anything from mechanics in his mathematical treatment of motion. A supplementary justification for that procedure was dictated later by the blind Galileo for inclusion in future editions.

Of the four dialogues contained in the book, the last two are devoted to the treatment of uniform and accelerated motion and the discussion of parabolic trajectories. The first two deal with problems related to the constitution of matter; the nature of mathematics; the place of experiment and reason in science; the weight of air; the nature of sound; the speed of light; and other fragmentary comments on physics as a whole. Thus Galileo’s *Two New Sciences* underlies modern physics not only because it contains the elements of the mathematical treatment of motion, but also because most of the problems that came rather quickly to be seen as problems amenable to physical experiment and mathematical analysis were gathered together in this book with suggestive discussions of their possible solution. Philosophical considerations as such were minimized.

The book opens with the observation that practical mechanics affords a vast field for investigation. Shipbuilders know that large frameworks must be strongly supported lest they break of their own weight, while small frameworks are in no such danger. But if mathematics underlies physics, why should geometrically similar figures behave differently by reason of size alone? In this way the subject of strength of materials is introduced. The virtual lever is made the basis of a theory of fracture, without consideration of compression or stress; we can see at once the inadequacy of the theory and its value as a starting point for correct analysis. Galileo’s attention turns next to the problem of cohesion. It seems to him that matter consists of finite indivisible parts, *parti quante*, while at the same time the analysis of matter must, by its mathematical nature, involve infinitesimals, *parti non quante*. He does not conceal—but rather stresses—the resulting paradoxes. An inability to solve them (as he saw it) must not cause us to despair of understanding what we can. Galileo regards the concepts of “greater than,” “less than,” and “equal to” as simply not applicable to infinite multitudes; he illustrates this by putting the natural numbers and their squares in one-to-one correspondence.

Galileo had composed a treatise on continuous quantity (now lost) as early as 1609 and had devoted much further study to the subject. Bonaventura Cavalieri, who took his start from Galileo’s analysis, importuned him to publish that work in order that Cavalieri might proceed with the publication of his own *Geometry by Indivisibles*. But Galileo’s interest in pure mathematics was always overshadowed by his concern with physics, and all that is known of his analysis of the continuum is to be found among his digressions when discussing physical problems.

Galileo’s *parti non quante* seem to account for his curious physical treatment of vacua. His attention had been directed to failure of suction pumps and siphons for columns of water beyond a fixed height. He accounted for this by treating water as a material having its own limited tensile strength, on the analogy of rope or copper wire, which will break of its own weight if sufficiently long. The cohesion of matter seemed to him best explained by the existence of minute vacua. Not only did he fail to suggest the weight of air as an explanation of the siphon phenomena, but he rejected that explanation when it was clearly offered to him in a letter by G. B. Baliani. Yet Galileo was not only familiar with the weight of air; he had himself devised practicable methods for its determination, set forth in this same book, giving even the correction for the buoyancy of the air in which the weighing was conducted.

Phenomena of the pendulum occupy a considerable place in the *Two New Sciences*. The relation of period to length of pendulum was first given here, although it probably represents one of Galileo’s earliest precise physical observations. Precise isochronism of the pendulum appears to have been the one result he most wished to derive deductively. In discussing resistance of the air to projectile motion, he invoked observations (grossly exaggerated) of the identity of period between two pendulums of equal length weighted by bobs of widely different specific gravity. He deduced the existence of terminal constant velocity for any body falling through air, or any other medium, but mistakenly believed increase of resistance to be proportional to velocity.

Like the pendulum, the inclined plane plays a large role in Galileo’s ultimate discussion of motion. The logical structure of his kinematics, as presented in the *Two New Sciences*, is this: He first defines uniform motion as that in which proportional spaces are covered in proportional times, and he then develops its laws. Next he defines uniform acceleration as that in which equal increments of velocity are acquired in equal times and shows that the resulting relations conform to those found in free fall. Postulating that the path of descent from a given height does not affect the velocity acquired at the end of a given vertical drop, he describes an experimental apparatus capable of disclosing time and distance ratios along planes of differing tilts and lengths; finally, he asserts the agreement of experiment with his theory. The experiments have been repeated in modern times, precisely as described in the *Two New Sciences*, and they give the results asserted. Following these definitions, assumptions, and confirmation by experiment, Galileo proceeds to derive a great many theorems related to accelerated motion.

In the last section Galileo deduces the parabolic trajectory of projectiles from a composition of uniform horizontal motion and accelerated vertical motion. Here the concept of rectilinear inertia, previously illustrated in the *Dialogue* (“Second Day”), is mathematically applied but not expressly formulated. This is followed by additional theorems relating to trajectories and by tables of altitude and distance calculated for oblique initial paths. Because of air resistance at high velocities, the tables assumed low speeds and hence were of no practical importance in gunnery. But like Galileo’s theory of fracture, they opened the way for rapid successive refinements at the hands of others.

Last Years. Galileo lived four years, totally blind, beyond the publication of his final book. During this time, he had the companionship of Vincenzio Viviani, who succeeded him (after Evangelista Torricelli) as mathematician to the grand duke and who inherited his papers. Viviani wrote a brief account of Galileo’s life in 1654 at the request of Leopold de’ Medici, which, despite some demonstrable errors, is still a principal source of biographical information, in conjunction with the voluminous correspondence of Galileo that has survived and with the autobiographical passages in his works. Near the end of his life, Galileo was also visited by Torricelli, a pupil of Castelli and the ablest physicist among Galileo’s immediate disciples. Galileo’s son, Vincenzio, also assisted in taking notes of his father’s later reflections, in particular the design of a timekeeping device controlled by a pendulum.

Galileo died at Arcetri early in 1642, five weeks before his seventy-eighth birthday. The vindictiveness of Urban VIII, who had denied even Galileo’s requests to attend mass on Easter and to consult doctors in nearby Florence when his sight was failing, continued after Galileo’s death: The grand duke wished to erect a suitable tomb for Galileo but was warned to do nothing that might reflect unfavorably on the Holy Office. Galileo was buried at Santa Croce in Florence, but nearly a century elapsed before his remains were transferred, with a suitable monument and inscription, to their present place in the same church.

Sources of Galileo’s Physics. The habitual association of Galileo’s name with the rapid rise of scientific activity after 1600 makes the investigation of his sources a matter of particular interest to historians of science.

All agree that Archimedes was a prime source and model for Galileo, who himself avowed the fact. The work of Aristotle and the pseudo-Aristotelian *Questions of Mechanics* were likewise admitted inspirations to Galileo, although often only as targets of criticism and attack. The astronomy of Copernicus and the magnetic researches of William Gilbert were obvious and acknowledged sources of his work. Beyond these, there is little agreement.

Among sixteenth-century writers, Galileo probably drew chiefly on Niccolò Tartaglia, Girolamo Cardano, and Guidobaldo del Monte. Parallels between his early unpublished work and that of Benedetti are very striking, but the establishment of a direct connection is difficult. As with the case of Stevin, the parallels in thought may result from the Archimedean revival and a common outlook rather than from early and direct knowledge of Benedetti's work.

Similarly, a direct influence of medieval writers on Galileo, although widely accepted by most historians, is still largely conjectured on the basis of specific parallels. The statics of Jordanus de Nemore was widely known in Italy after 1546, when Tartaglia published in Italian and endorsed the "science of weights" as necessary to an understanding of the balance; yet all subsequent writers (at least in Italy) condemned it in favor of the Archimedean approach. Writings of the Merton school, published repeatedly in Italy up to about 1520, continued to be discussed thereafter at Paris and in Spain. Galileo's reasoning about acceleration, after his recognition of its importance around 1602, invariably proceeded by comparison of ratios, whereas medieval writers adopted a mean speed as representative of uniformly changing velocities. Medieval impetus theory, which Galileo adopted at first for the explanation of projectile motion, had no place in the concept of neutral motions that led him eventually to an inertial terrestrial physics. A connection of Galileo's own physical thought with medieval sources may yet be convincingly established, but at present this has not been done.

Experiment and Mathematics. The role of experiment in Galileo's physics was limited to the testing of preconceived mathematical rules and did not extend to the systematic search for such rules. It is probable that his use of experiment had its roots in the musical controversy conducted by his father rather than in philosophical considerations of method. Appeal to experiment in his published works was resorted to by Galileo chiefly as a means of confuting rival theories, as in the dispute over bodies in water and in his rejection of proportionality of speed to space traversed in free fall.

It is difficult to find older sources for Galileo's attitude toward mathematics, which was strikingly modern. He considered mathematics to enjoy a superior certainty over logic. Where a mathematical relation could be found in nature, Galileo accepted it as a valid description and discouraged further search for ulterior causes. He attributed discrepancies between mathematics and physical events to the investigator who did not yet know how to balance his books. Galileo did not adopt the traditional Platonist view that our world is a defective copy of the "real" world, and he derided philosophical speculation about a world on paper.

The Influence of Galileo. Except with respect to the acceptance of Copernican astronomy, Galileo's direct influence on science outside Italy was probably not very great. After 1610 he published his books in Italian and made little effort to persuade professional scholars either at home or abroad. His influence on educated laymen both in Italy and abroad was considerable; on university professors, except for a few who were his own pupils, it was negligible. Latin translations of his *Dialogue* appeared in Holland in 1635, in France in 1641, and in England in 1663; but the only Latin translation of the *Two New sciences* was published in 1700, long after Newton's *principia* had superseded it.

Between Galileo and Newton, science was Cartesian rather than Galilean. Indirectly, Galileo's science exerted some influence in France through Marin Mersenne, Pierre Gassendi, and Nicholas Fabri de Peiresc; in Germany through Kepler; and in England through John Wilkins and John Wallis. Descartes, who repudiated Galileo's approach to physics because of its neglect of the essence of motion and physical causation, did not mention him in any published work. Newton seems not to have read Galileo's *Two New Sciences*, at least not before 1700, but knew his *Dialogue* as early as 1666. Aware of his achievements in physics only indirectly, Newton, in the *Principia*, mistakenly credited Galileo with a derivation of the laws of falling bodies from the law of inertia and the force-acceleration relationship.

Within Italy, Galileo had a strong following both in scientific and nonscientific circles. His ablest pupil, Castelli, was the teacher of Torricelli and Cavalieri, both of whom also had personal acquaintance with Galileo. His last pupil, Viviani, did much to extend Galileo's influence in the succeeding generation, editing the first collection of his works in 1655–1656. But by that time physics and astronomy had both progressed well beyond the point where Galileo had left them.

Outside scientific circles, Galileo's influence was strongly felt in the battle for freedom of inquiry and against authority. English translations of his *Dialogue* and *Letter to Christina*, published in 1661, carried this influence outside academic circles. John Milton cited the fate of Galileo in his *Areopagitica*. French writers during the Enlightenment also made Galileo a symbol of religious persecution.

Personal Traits. Galileo was of average stature, squarely built, and of lively appearance and disposition. Viviani remarks that he was quick to anger and as quickly mollified. His unusual talents as a speaker and as a teacher are beyond question. Among those who knew him personally, even including adversaries, few seem to have disliked him. Many distinguished men became his devoted friends, and some sacrificed their own interests in his support at crucial periods. On the other hand, there were many contemporary rumores discreditable to Galileo, and demonstrable slanders occur in letters of Georg Fugger, Martin Horky, and others. Pugnacious rather than belligerent, he refrained from starting polemic battles but was ruthless in their prosecution when he answered an attack at all. His friends included artists and men of letters as well as mathematicians and scientists; cardinals as well as rulers; craftsmen as well as learned men. His enemies included conservative professors, several priests, most philosophers, and those scientists who had publicly challenged him and felt the bite of his sarcasm in return.

Caution and daring both had a place in Galileo's personality. His reluctance to speak out for the Copernican system until he had optical evidence against the rival theories is evidence of scientific prudence rather than of professorial timidity. Once convinced by his own eyes and mind, he would not be swayed even by the advice of well-informed friends who urged him to proceed with caution. In the writings he withheld from publication, as in his surviving notes, many errors and wrong conjectures are to be found; in his published works, very few. He was as respectful of authority in religion and politics as he was contemptuous of it in matters he could investigate for himself. It is noteworthy that before his Copernican stand was challenged by an official Church edict, he had composed and submitted to the authorities a carefully documented program, based on positions of Church fathers, that would have obviated official intervention against his science—a program that was in fact adopted by a pope nearly three centuries later as theologically sound.

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Stillman Drake

Galilei, Galileo

Complete Dictionary of Scientific Biography

(*b*. Pisa, Italy, 15 February 1564; *d*. Arcetri, Italy, 8 January 1642),

physics, *astronomy, philosophy of science*. For the original article on Galileo see *DSB*, vol. 5.

Since the publication of Stillman Drake's *DSB* entry on Galileo in 1972, Galilean studies have come a long way. New translations have made Galileo's works accessible to a large, multinational reading public. New critical editions of his texts, in many cases complemented by a sophisticated apparatus and explanatory comments, have helped to provide a more profound appraisal of his splendid prose. Above all, a host of studies on nearly every aspect of Galileo's life and accomplishments have deepened scholars' understanding of his eminent intellectual legacy. As a rough indication as of 2007 of the number of studies on Galileo published after Drake's *DSB* article, suffice it to say that the *International Galilean Bibliography* (edited by the Institute and Museum of History of Science in Florence) counts more than 6,100 post-1972 records.

Thanks to this vast number of studies scholars are in a position to assess from a sounder historical standpoint the many facets of Galileo's achievements. Even though the results of these studies do not significantly affect the excellent outline provided by Drake, subsequent works have added pieces of information that deserve to be taken into account in order to achieve a more comprehensive appraisal of Galileo's accomplishments.

Editions . A noteworthy feature of Galilean studies since the 1970s is the publication of new, often outstanding editions of Galileo's works. Of special value are the *Sidereus nuncius* edited by Isabelle Pantin (with French translation and very detailed notes) and the critical editions of the *Dialogue on the Two Chief Systems*, the *Discourse on the Comets*, and *The Assayer* prepared by Ottavio Besomi and Mario Helbing. All these editions couple philological exactitude with extensive and accurate commentaries. Of great interest for Galilean scholars is the edition of the proceedings of Galileo's trial by Father Sergio Pagano, which adds to the known documentation some materials not included in the Edizione Nazionale (National Edition) of Galileo's works.

Readers in English have increased opportunities to read Galileo's texts thanks to improved or fresh translations. In 1974 Stillman Drake replaced the old version of the *Two New Sciences* by Henry Crew and Alfonso De Salvio (first issued in 1914) with a subsequent, more careful one. Further, in 1977 William Wallace translated from the Latin *Galileo's Early Notebooks*(the so-called *Juvenilia*), and in 1989 Albert Van Helden edited a remarkable English *Sidereus nuncius* (*The Sidereal Messenger*). In the same year, Maurice Finocchiaro translated the most relevant documents pertaining to the “Galileo affair,” comprising the theological letters to Benedetto Castelli, Piero Dini, and Grand Duchess Cristina, as well as the *Discourse on the Tides* (1616) and the *Reply to Francesco Ingoli* (1624). Eight years later, in 1997, Finocchiaro also published a large collection of excerpts from Galileo's *Dialogue*, which he complemented with explanatory notes.

Editorial work has also been actively engaged with Galileo's unpublished texts. This has been the case notably with the logical notes of Manuscript 27 of the Galilean Collection in the National Library of Florence, which were integrally edited by William F. Edwards and William Wallace in 1988 under the title *Tractatio de praecognitionibus et praecognitis and Tractatio de demonstratione*. Wallace also provided an English translation of these treatises, emphasizing their importance for the development of Galileo's scientific methodology.

Another remarkable edition concerns the Galilean Manuscript 72, whose contents show the evolution of Galileo's thought on mechanics from his early years in Padua to the printing of *Two New Sciences* in 1638. Under the title *Galileo Galilei's Notes on Motion*, the Central National Library (Florence), the Institute and Museum of History of Science (Florence), and the Max Planck Institute for the History of Science (Berlin) have carried out an innovative project, publishing on the Internet an electronic reproduction (accompanied by transcriptions and apparatus) of this manuscript. The Institute and Museum of History of Science in Florence has also edited a Web archive, *Galileothek@*, which offers texts of all of Galileo's works as well as images, bibliographical records, lexicographical and thematic indexes, sections devoted to experiments, and a detailed Galilean chronology, along with powerful tools for searching and navigating through the various repositories.

Finally, it should be added that a project of updating the masterful twenty-volume National Edition of Galileo's *Works* (*Opere*), edited by Antonio Favaro and published between 1890 and 1909, was initiated in 2006. This project, anticipated to be completed by 2010, includes the publication of several volumes devoted to all those Galilean materials (works, letters, documents) that were unknown to Favaro and accordingly were not included in his edition.

Jesuit Sources . One of the most interesting debates surrounding Galileo concerns the sources of the above-mentioned notes on logic (Galilean Manuscript 27) and of the treatises edited by Favaro under the title *Juvenilia*. A few scholars (Alistair Crombie, Adriano Carugo, and William Wallace) have argued that these texts are based on works of Jesuit authors. As the specific sources of Galileo's *Juvenilia* they name Franciscus Toletus's commentaries (1573 and 1575) on Aristotle's *Physics* and *De generatione et corruptione*, Benedictus Pererius's textbook *De communibus omnium rerum naturalium principiis et affectionibus*(1576), and the commentary on Sacrobosco's *Sphere* by the distinguished Jesuit astronomer Christopher Clavius (1581). More controversial is the identification of the precise texts said to have inspired the notes on logic of Galileo's Manuscript 27. Crombie and Carugo held that Galileo relied on a printed book (Ludovico Carbone's *Additamenta ad commentaria D. Francisci Toleti in Logicam*, 1597), while Wallace has maintained that the real source of these Galilean comments on Aristotle's *Posterior Analytics* was a manuscript *reportatio* of the logic course offered at the Collegio Romano by the Jesuit professor Paolo Della Valle during the academic year 1587–1588. Though no copy of this manuscript is extant, Wallace holds that its contents were plagiarized by Ludovico Carbone, a circumstance that would account for the resemblances between Galileo's Manuscript 27 and Carbone's *Additamenta*.

On these grounds, Wallace has emphasized the crucial role played by Aristotelian logic and methodology for Galileo's achievements, adding that the alleged strong epistemological continuity perceptible in Galileo's scientific evolution is the result of his unwavering reliance on the Aristotelian demonstrative method he learned from the Jesuit commentaries. Wallace's conclusion is in fact quite bold, arguing that “Galileo's methodology was already spelled out in the treatises he appropriated from the Collegio Romano” (1992, p. xvi). Although it is not possible to provide here a detailed survey of Wallace's arguments, it must be observed that, apart from its pronounced conjectural character—there is no compelling evidence of Galileo's use of the Collegio Romano's materials—Wallace's reconstruction obscures Galileo's vehement anti-Aristotelian polemic, which actually forms a substantial part of his accomplishments.

As antidote to such a “pan-logical” view of Galileo's epistemology, one should also bear in mind what Galileo claims in the “Second Day” of the *Two New Sciences*: “It seems to me that logic teaches how to know whether or not reasonings and demonstrations already discovered are conclusive, but I do not believe that it teaches how to find conclusive reasonings and demonstrations” (Drake trans., 2nd edition, 1989, p. 133).

Galilean Manuscript 72 . As a central contribution to modern science, Galileo's theory of motion has always attracted much scholarly attention. In the last decades of the twentieth century a more precise assessment of the development of Galileo's views on this matter became possible thanks to more careful studies of the scraps of Manuscript 72.

It is known that Galileo had planned to write a treatise on motion prior to his discoveries with the telescope in the 1609–1610 period. In May 1610 he wrote to the secretary of the Grand Duke of Tuscany, Belisario Vinta, that he was about to bring to completion “three books on local motion, an entirely new science, no one else, ancient or modern, having discovered some of the very many admirable properties that I demonstrate to exist in natural and forced motions” (*Opere*, Edizione Nazionale a cura di A. Favaro, Florence: Giunti Barbera, 1890–1909, repr. 1968, X, pp. 351–52). However, because Galileo embarked on different scientific pursuits and became involved in a number of scientific disputes, he was unable to bring out his “new science of motion” before 1638, when he published the *Two New Sciences*. Manuscript 72 constitutes a kind of filing cabinet in which Galileo saved the drafts of the theorems that he was to include in his *Two New Sciences*, along with numerous textual fragments, drawings, and calculations related to his mechanical research. Because they cover a period of nearly forty years, the materials of the codex are of the utmost importance for a more precise appraisal of Galileo’s route to his final theory of motion. For this reason, Galileo scholarship has paid increasing attention to Manuscript 72.

A remarkable result of these studies concerns clues in Manuscript 72 that indicate Galileo carried out an extensive experimental program. Several diagrams and calculations contained in the codex seem to provide evidence that, since the earliest years of the seventeenth century, Galileo performed experiments by rolling balls down planes inclined at small angles to the horizontal and by studying the swings of pendulums of different lengths. Although scholars have proposed different interpretations and chronologies of its contents, consensus exists that several folios of Manuscript 72 record experimental data. This evidence strongly reinforces the thesis that an important part of Galileo’s accomplishments in mechanics was rooted in experimentation.

Thus, while in his entry for the *DSB* in 1972 Drake wrote that “the role of experiment in Galileo’s physics was limited to the testing of preconceived mathematical rules and did not extend to the systematic search for such rules” (p. 247), seven years later, in 1979, he argued that the contents of Manuscript 72 bear out the conclusion that “Galileo found the law of free fall by experiment, or rather by the making of very careful measurements” (1979, p. x).

Nevertheless, it is still difficult to ascertain whether Galileo resorted to experiments merely to confirm the results he had already obtained via mathematical reasoning or whether the experimentation itself played a role in obtaining the results. At any rate, relying on careful survey of the contents of Manuscript 72, one can confidently assume that experimental practice was an essential constitutive element of Galileo’s “new science of motion.”

Atomism and the Eucharist . In section 48 of *The Assayer*(1623), Galileo set forth a theory of knowledge based on a sharp distinction between “objective” and “subjective” qualities. According to this view, whereas features such as shape, size, position, motion, and number are qualities intrinsic to real things, impressions such as colors, tastes, smells, or tactile properties do not exist in the objects themselves but only in the sentient subject experiencing them. For this reason, sensible qualities were characterized by Galileo as “mere names,” qualities that “reside only in the consciousness” and that would be “wiped away and annihilated” once human sensibility is removed. Behind sensible qualities are the true components of the real world, atoms, whose impinging on the sense organs produces sensory impressions. Hence, for example, the sensation of heat stems from the motion of a “multitude of minute particles” that penetrate human bodies; “their touch as felt by us when they pass through our substance is the sensation we call ‘heat.’” (trans. in Drake, *Discoveries and Opinions of Galileo*, New York: Anchor Books, 1957, p. 277). Galileo’s stance was clearly rooted in the tradition of ancient atomism, whose most distinguished representatives, such as Democritus and Lucretius, had already stated similar views.

Two documents discovered in the Archives of the Congregation for the Doctrine of the Faith (formerly Holy Office) show that Galileo’s atomistic theory was brought to the attention of the Inquisitorial authorities, most likely before the trial of 1633. The first document was found in 1982 by Pietro Redondi and is usually referred to as “G3,” from the code appearing on the top of its first page. G3 is a denunciation of the atomism of *The Assayer*. The anonymous author protested that Galileo’s interpretation of sensible qualities clashed with the Catholic doctrine of the Eucharist, according to which, after consecration in the Mass, bread and wine become the body and blood of Jesus Christ. This transformation is understood as transubstantiation because it concerns the substances of bread and wine, whereas their “accidents,” or apparent qualities (color, odor, exterior shape), remain unchanged by virtue of a divine miracle. The author of G3 remarked that, according to the terms of Galileo’s argument, it would be impossible to separate the accidental properties of bread and wine from their own substances. Indeed, because those accidental properties are regarded as “mere names” and as nonexistent outside human sensory perception, on the basis of Galileo’s theory one would be obliged to conclude that “in the Sacrament there are substantial elements of the bread and the wine, which is an error condemned by the Sacred Council of Trent.”

Redondi dated G3 to 1624 and attributed it to Orazio Grassi, the Jesuit mathematician against whom Galileo had written *The Assayer*. Redondi also connected the document to the trial of 1633, suggesting that the charge of Copernicanism that motivated the trial was a stratagem devised by Pope Urban VIII (a former friend of Galileo) in order to avoid having the scientist face the more serious accusation of Eucharistic heresy.

Redondi’s ascription of G3 to Grassi has been proved to be mistaken, and his thesis concerning the “true” (although disguised) reasons of the trial has been generally rejected by scholars. Nevertheless, Redondi’s book triggered a fresh wave of interest in the Galileo affair and renewed investigations into its cultural and political context.

Another document, similar to G3, was discovered by Mariano Artigas in 1999 and has been carefully studied by Artigas himself along with Rafael Martinez and William Shea. This document is placed in the same volume as G3, the volume EE of the collection “Acta et Documenta,” where it occupies sheet 291. For this reason it has been called “EE 291.”

Like G3, EE 291 is anonymous (it is in Latin while the former is in Italian), and it equally develops a criticism of the theory of sensible qualities expounded in *The Assayer*, which it deems incompatible with the doctrine of the Eucharist. The author of this document has been identified as the Jesuit Melchior Inchofer, who probably was a member of the commission appointed by the pope in the summer of 1632 to examine Galileo’s *Dialogue*. Inchofer, a firm opponent of Copernicanism, could have written EE 291 in order to worsen Galileo’s position by adding a further charge against him. Thus, the discoveries of G3 and EE 291, besides providing valuable pieces of information on previously unknown episodes of Galileo’s life, also opened a new chapter of investigation concerning the difficult relationship between atomism and Eucharistic doctrine.

The Role of Patronage . It is well known that Galileo spent a great part of his mature life, from 1610 until his death in 1642, at the Medici court as mathematician and philosopher of the Grand Duke of Tuscany. Furthermore, even before his return to Florence from Padua (in the autumn of 1610), Galileo had to deal with several patrons in order to promote his career and to obtain academic positions. Indeed, the practice of relying on the support of influential patrons was quite normal at the time. As Richard S. Westfall remarked: “Patronage was perhaps the most pervasive institution of preindustrial society” (1985, p. 29); hence: “the system of patronage […] was a feature of 17th century life as distinctive as scientific technology is in the 20th century” (1984, p. 200).

For this reason, the last decades have witnessed a growing interest in re-interpreting Galileo’s life and achievement in the light of the patronage culture. Richard S. Westfall focused on the role played by patronage in Galileo’s relationship with the Accademia dei Lincei (1984) and the Jesuit order (1988) as well as in the controversial episode of the discovery of the phases of Venus (1985), while Frederick Hammond provided a fascinating outline of the connection between Pope Barberini’s system of patronage and the Galileo affair.

But the most comprehensive study on this matter is certainly Mario Biagioli’s seminal book, *Galileo Courtier*. Biagioli argues that “Galileo’s courtly role was integral to his science” (1993, p. 1), because “the court contributed to the cognitive legitimation of the new science by providing venues for the social legitimation of its practitioners” (1993, p. 2). Actually, courtly patronage being “the social world of Galileo’s science” (1993, p. 4), the latter was involved in a process of self-fashioning, aimed to work out a fresh social and intellectual image, best fitted to courtly codes and rules. In this process, Galileo “used the resources he perceived in the surrounding environment to construct a new socio-professional identity for himself, to put forward a new natural philosophy, and to develop a courtly audience for it” (1993, p. 5). In short, Biagioli views Galileo “not only as a rational manipulator of the patronage machinery but also as somebody whose discourse, motivations, and intellectual choices were informed by the patronage culture in which he operated throughout his life” (1993, p. 4).

Biagioli’s detailed account (based on detailed documentation from primary and secondary sources) mainly concerns Galileo’s experience at the Medici court, spanning from 1610 to just after the 1633 trial. The core of his interpretation relies on the assumption that the social legitimation Galileo acquired in the courtly *milieu* assured the cognitive legitimation of his theories.

While innovative and appealing, Biagioli’s historio-graphical proposal runs the strong risk of being sometimes unreliable and implausible. For example, Biagioli views Galileo’s Copernican commitment as an outcome of a strategy based on the logic of patronage. As he puts it: “Copernicanism was the ‘natural’ choice for someone such as Galileo who aspired to a higher socioprofessional status, while the court was the social space that could best legitimize such an unusual socioprofessional identity” (1993, p. 226). Hence, “the increasing commitment to Copernican astronomy that Galileo developed in those years [i. e. after 1609–1610] may have resulted also from the patronage dynamics that pushed him to defend his discoveries and produce even more of them” (1993, p. 91).

This seems an oversimplified account of the motivations that drove Galileo to embrace the Copernican theory, because it completely ignores the theoretical reasons behind his choice, which were rooted in the interplay between astronomical arguments and the principles of Galileo’s “new science of motion.” Indeed, by reducing the cognitive acceptance of science to its social legitimation, Biagioli tends to obscure the autonomy of scientific debate. Consequently, he often disregards the multifaceted complexity of history, failing to recognize that ideas follow their own paths, connected to, but not always dependent on, social features.

The Galileo Affair Revisited . On 10 November 1979, on the occasion of the one hundredth anniversary of the birth of Albert Einstein, before a plenary session of the Pontifical Academy of Sciences, Pope John Paul II delivered an address on the “deep harmony that unites the truths of science with the truth of faith” (*L’Osservatore Romano*, English week edition, November 26, 1979, pp. 9–10). In his speech John Paul II dealt with the trial and condemnation of Galileo, frankly admitting that the scientist “had to suffer a great deal at the hands of men and organs of the Church.” John Paul II expressed the hope that “theologians, scholars and historians, animated by a spirit of sincere collaboration, will study the Galileo case more deeply and, in loyal recognition of wrongs from whatever side they come, will dispel the mistrust that still opposes, in many minds, a fruitful concord between science and faith.”

As a consequence of this wish, in July 1981, the Vatican constituted a study commission divided into various sections (exegetical, cultural, scientific-epistemological, and historical-juridical). The commission met several times, held a few conferences, and issued a significant number of publications. Its work was declared to be concluded on 31 October 1992, at an audience given by the pope at a plenary session of the Pontifical Academy. On that occasion the pope underlined Galileo’s mistake in not presenting the Copernican system as a hypothesis, because “it had not been confirmed by irrefutable proofs” (trans. in Fantoli, 2003, p. 370). Yet John Paul II acknowledged that Galileo’s views on scriptural interpretation were sounder than those put forth by the theologians of his epoch. The pope also claimed that the Galileo affair resulted from a “tragic mutual incomprehension” that would have poisoned the subsequent relationship between faith and science, creating the myth of the Church’s opposition to the free search for truth. He concluded that “the clarifications furnished by recent historical studies enable us to state that this sad misunderstanding now belongs to the past.”

John Paul II’s words were of the highest importance, marking a break with the Church’s long-held attitude toward Galileo by honestly recognizing the errors committed by the Catholic Church. Nevertheless, some of the arguments put forth by John Paul II suggested a defensive strategy not consonant with that “loyal recognition of wrongs from whatever side they come.” It is misleading to blame Galileo for his refusal to consider Copernicanism as a hypothesis while emphasizing his alleged inability to provide definitive evidence in support of the Copernican theory. Indeed, Galileo did not regard Copernicanism as a purely mathematical expedient to predict celestial events. According to his view, in fact, a system of the world should account for the true structure of the universe. At the same time, Galileo was firmly convinced of having good reasons in support of Copernicanism, because observations and theoretical explanations (not only his mistaken theory of tides, but also his new science of motion) confirmed to him that the arguments for the Earth’s motion were much stronger than those against it.

Still, it must be remembered that Galileo was not condemned for the inadequacy of his scientific or epistemological position but for exegetical considerations pertaining to the clash between heliocentrism and several passages of the Bible. The epistemological concerns raised by John Paul II were never addressed by the Roman inquisitors, who only focused on the theological consequences of Galileo’s Copernicanism.

In conclusion, the Galileo affair is by no means a closed question and continues to be a promising field for historical investigation. Many of its most obscure facets are as of 2007 still in need of clarification, and it also deserves to be carefully and constantly pondered for its worth as a significant memento. As Annibale Fantoli has observed, the Galileo affair “remains, and should remain, ‘open’, as a severe lesson of humility to the Church at all levels and as a warning, no less rigorous, not to wish to repeat in the present or in the future errors similar to those which have brought about [such a] heavy burden” (2003, p. 373).

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