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6
Galileo

Early Works

Galileo Galilei was born in Pisa, Italy on February 15, 1564. His Florentine father, Vincenzio Galilei, was a merchant and an accomplished musician and music theorist. His mother, Giulia Ammannati, was from neighboring Pescia. Though Galileo enrolled in the University of Pisa in 1581 with the intention of studying medicine, he studied mathematics instead. In 1585 he left the university before completing his degree. The first fruit of his interest in physics and the Archimedean method was *Theoremata circa centrum gravitatis solidorum*. Basing his work on Archimedes, he designed a hydrostatic balance in 1586 and wrote *La bilancetta*.

Galileo's first job as professor of mathematics at the University of Pisa came in 1589 thanks to the influence of Guidobaldo del Monte with the Grand Duke Ferdinand. It was during his tenure at Pisa that Galileo wrote *De Motu* (ca. 1592), a work in which he made the anti-Aristotelian claim that all bodies are intrinsically heavy and lightness is simply relative: for instance, flames rise not because they possess the characteristic of lightness but because they are lighter than air. In this same work Galileo discussed the velocity of different bodies in a like medium, as well as like bodies in different mediums and different bodies in different mediums. He was not trying to prove that all bodies fall at the same speed, but that the speed of the fall of a body is proportional to the difference between its own weight and the density of the medium through which it falls. Like objects that are equally dense will fall through the air at the same speed, regardless of their weight. However, if two objects of equal weight but different composition were dropped at the same time, the denser object will fall faster. So, contrary to Aristotle, given the progressive reduction in the density of the medium, motion in a vacuum is indeed possible and objects made of different materials fall through it at different speeds.

This work marked the beginning of a long journey which ultimately led Galileo to reject Aristotelianism. He worked on a variety of problems over the next fifty years: the isochronism of a swinging pendulum; falling bodies; projectile motion; cohesion; the strength of materials; "impulsive" or impetus force. His theories and methods changed many times over the course of this half century as he incorporated corrections, a deeper understanding of the problems, and even conceptual developments into his work. One element which remained constant, however, was a tacit acceptance of both the approach and method of the "divine Archimedes."

Galileo's interest in technical problems, first expressed in *La bilancetta*, continued even after he became a professor of mathematics at the University of Padua in 1592. Between 1592 and 1593 he wrote three works – *A Brief instruction in military architecture*, *On Fortifications*, and *On Mechanics* – which were not even published until 1634, and then in French by Mersenne. He lectured on Euclid's *Elements* and Ptolemy's *Almagest*. In 1597, he wrote *Treatise on the Sphere, or Cosmography*, a clearly worded guide to the geocentric system for students. Yet he was already following a different path. In a letter to Kepler that same year, he revealed that he had long been a convert to Copernicanism even if he had not yet dared publish his findings out of fear of what had befallen their common master. Nor did he abandon his other interest. The instruments he needed for his lessons and other pursuits were all crafted in a small workshop next to his study. From the workshop came objects related to his work on military architecture and fortifications, ballistics, hydraulic engineering, in addition to instruments for his research on the strength of materials, the construction of the geometrical and military compass, the telescope, and thermo-baroscope. His passion for observation, measurement and instruments never abated, nor did his infinite curiosity for experiments. He published a pamphlet about the *Geometrical and Military Compass* in 1606, and the next year wrote the *Defense against the deception and fraud of Baldessar Capra*, who had falsely claimed to be the inventor of the compass.

Astronomical Discoveries

The year 1609 was important in the history of science. The great astronomical discoveries of the year (the *Sidereus nuncius* appeared in 1610) not only undermined a consolidated view of the world but also weakened the claims against the Copernican system. To begin with, the moon

was terrestrial in nature and nonetheless *moved* through the sky: from this perspective, it was no longer ludicrous to suggest that the Earth, too, moved. What was more, Jupiter and its revolving satellites suddenly appeared to be a small-scale version of the entire Copernican system. Observation of the fixed stars revealed that they were much farther away from the Earth than the planets were, and they did not appear to be located directly behind the sky of Saturn. The absence of an observable parallax of the stars had been one of the biggest objections to the Copernican system. Parallax is the change in position that occurs when the same object is observed from different places (if you look at a pencil with one eye closed and then open that eye and close the other, the pencil looks like it has moved). The greater the distance the smaller the change should be. The objection advanced by Tycho, among others, was this: if the Earth moved through space, the shape of the constellations should change from season to season. The impossibility of detecting stellar parallax could now be explained by the vast distance that separated the stars and the Earth.

Fresh evidence in support of the Copernican system and against the Ptolemaic came in the form of the astronomical observations made by Galileo shortly before leaving the University of Padua for a court appointment in Florence as "Chief Philosopher and Mathematician to the Grand Duke" in September 1611. He had observed the "tricorporeal" appearance of Saturn (the "rings" were not visible through his telescope), sunspots, and the phases of the planet Venus. The observation that Venus "showed phases just like the moon" rightfully struck Galileo as significant. Indeed this revealed a situation which in no way fit a Ptolemaic scheme of the world nor could be explained by it.

In a letter to Cesi in May 1612, Galileo announced that the "novelty" of the sunspots he had discovered was the "death or rather last judgment of pseudo-philosophy." The changing shape and disappearance of the spots on the very surface of the sun, he later explained in the *History and Demonstration Concerning Sunspots and their Phenomena*, were not an obstacle to "freethinkers" who had never believed that the heavens beyond the sublunar sphere were immutable (Galilei, 1890–1909: V, 129).

Following the great astronomical discoveries of 1610, Galileo threw all caution to the wind. He wrote to Giuliano de Medici in January 1611 that "we have sensory experiences and necessary demonstrations for two problems that until now have remained unresolved by the greatest thinkers of the world" (ibid.: XI, 12). One was that planets were opaque bodies, and the other that they rotated around the sun. While the Pythagoreans, Copernicus, Kepler, and Galileo himself had "believed" this to be true, it had never been "reasonably proved." Kepler and other Copernicans could now glory in the knowledge of "having believed and philosophized well, even though we have been and still are considered by all *in libris* philosophers to not be very knowledgeable and little more than fools" (ibid.: XI, 12).

In hopes of securing the court appointment he so desired – chief philosopher in addition to chief mathematician – Galileo wrote to the grand duke's secretary of state describing his future projects almost immediately after the *Starry Messenger* was published. He said that he was planning two books on the system and the constitution of the universe; three books on local motion ("an entirely new science in which no one else, ancient or modern, has discovered any of the remarkable laws which I demonstrate"); three books on mechanics; and even works on sound, the ocean tides, the nature of continuous quantities, and the motion of animals. The new astronomy and physics would not only prove Copernicanism but also establish a new science of nature. To the "viper-like obstinacy" of academic philosophers and professors, Galileo now proudly proposed his own philosophy and declared that he had "studied more years of philosophy than months of pure mathematics" (ibid.: X, 353).

Galileo's remarkable confidence owed something to the fact that he was indeed appointed Chief Philosopher and Mathematician to the Grand Duke of Tuscany in September 1611 (and so moved from Padua to Florence). In light of recently discovered documents, his decision to leave Padua was actually rife with consequences. Until the 1992 discovery by Antonino Poppi of an earlier document, it has long been accepted that the Rome Holy Office first expressed concern about Galileo and his work during the congregation of May 17, 1611, when it was explicitly asked if Galileo had been mentioned in the proceedings against Cesare Cremonini. The Poppi document instead shows that seven years earlier, on April 21, 1604, "he had been formally accused of heresy and libertine customs by the Inquisition of Padua." Although the informer (most likely Silvestro Pagnoni, Galileo's scribe) admitted that "in matters of faith I had never heard him say anything negative," he accused him of casting horoscopes, failing to attend mass and receive the sacrament, having a lover, and reading unedifying books. "I learned from his mother," states the informer, "that he never went to confession or took holy communion, and she sometimes made me check to see if he attended mass on feast days; but instead of going to mass he would visit the Venetian whore Marina, who lives at Pontecorvo." (The woman to whom he referred is Marina Gamba, who bore Galileo three children between 1601 and 1606: Virginia, Livia, and Vincenzo.) He added, "I believe that his mother has gone to the Florence Holy Office against her son's wishes, and that he called her unspeakably rude names like whore and *gabrina*." If this last statement is indeed true, then Galileo was first denounced to the Inquisition as early as 1592.

In light of this new information, it would certainly seem that Galileo's move from Padua to the Tuscan court was not such a wise one. The Paduan professors who ultimately came under the suspicion of the Inquisition were strenuously defended by the Venetian Republic. The defense argued that "these accusations have been made by ill-meaning and self-interested souls [. . .] For this sound reason, and the knowledge that the reputation of the University will suffer, and divisions and disputes will arise among the students, we are moved to recommend that in Your customary prudence and sagacity You proceed no further in the investigation of these claims."

Admittedly, *if only* is a not a good phrase to use in the writing of history, but the evidence we have today surely sheds new light on Cremonini's words: "Oh, it would have been so much better if only Signor Galileo had not gotten involved in all this intrigue and had never left his Paduan freedom" (Poppi, 1992: 11, 58–60, 26–7, 62–3).

Galileo's sense of security was at any rate also tied to the events that followed his move to Florence. He was triumphantly received by scholars and clergy alike during his visit to Rome in 1611: he was elected to the *Accademia dei Lincei*, and was approvingly received by respected cardinals, the Jesuits, and Pope Paul V himself. In December 1612, Galileo felt nothing but hope and optimism. Yet storm clouds were gathering at that very moment. Galileo wrote a series of "letters" that were meant to persuade and convince a public of the new truths. However, in his optimism Galileo failed to detect the great cultural and "political" implications of the controversy over Copernicanism. He seemed sure, at the time, that victory was close at hand and believed he faced the ignorance and self-conceit of only individuals. He was unaware of both growing opposition in certain ecclesiastical circles and the general implications of his own position. He alternated between extreme confidence and an unchecked tendency to be controversial, rhetorical, and quick to find fault.

Nature and the Bible

It was not as if Galileo had not received warnings and advice to be cautious. Paolo Gualdo wrote him to "think twice before you publish this your opinion as fact, because many things can be said for the sake of argument that it would not be wise to assert as true." From the pulpit of St. Mark's monastery in Florence on the Day of the Dead in 1612, the Dominican Nicholas Lorini preached a sermon accusing Copernicans of heresy. At the end of the following year, Galileo's friend and faithful disciple Benedetto Castelli defended the doctrine of the Earth's mobility before the Grand Duke and his mother, the Grand Duchess Christina.

The growing controversy, along with a fear of losing favor with the Medicis, persuaded Galileo to direct action. His 21 December 1613 *Letter to Castelli*, widely circulated, explicitly addressed the question of the compatibility of Scriptural and scientific truth.

The text of the *History and Demonstration Concerning Sunspots and their Phenomena*, published by Prince Cesi that same year, was significantly censored. Galileo had written that the theory of the incorruptibility of the heavens was not only false but "erroneous and repugnant to the unquestionable truths of the Sacred Word which tells us that heavens and the whole world [. . .] were generated, dissolvable, and transitory." Cesi had to tell Galileo that the church's censors "having approved all the rest, want no part of this" (Galilei, 1890–1909: V, 238; XI, 428–9). The final approved version of the *Letter on Sunspots* contained no references to the Bible.

Scriptural decrees, wrote Galileo in the letter, are absolute and inviolable truths. Scripture is never wrong, though those who interpret it can make mistakes, especially when statements have been adapted for the easier comprehension of the Hebrews. As for the "naked sense of the word," many statements therefore appear "different from the truth," and have been adapted for the comprehension of ordinary people and require explanation by the wise interpreters. Nature and Scripture both proceed from the Word of the Lord: the first as the dictate of the Holy Spirit" and the second as "the faithful executrix of God's commands." However, while the language of Scripture has been adapted so that men may understand it and so its words may have different meanings, nature is instead "inexorable and immutable" and does not care if its causes and functions are "clearly grasped by man's intellect." In discussions about nature, Scripture "should be reserved to the last place." Nature has a logic and discipline not found in Scripture: "the Bible is not chained in every expression to conditions as strict as those which govern all physical effects." The "physical effects" that sensory experience sets before us can never be "revoked upon the testimony of Biblical passages which may have some different meanings." The task of the "wise interpreter of the divine text" (given that nature and Scripture can never contradict one another) is to "work hard to find the true sense of sacred passages" that agree with demonstrated scientific results. Moreover, given that Scripture admittedly is metaphorical, and that we are not in fact certain all its interpreters were divinely inspired, it would be prudent to allow no one to use Scriptural passages as proof of physical phenomena which could, in the future, be shown to be false. Scripture tends to persuade men of truths necessary for their own salvation, but it is not necessary to believe that what we know to be true through the senses and the mind has been given to us by Scripture. The second (and much briefer) part of the letter argues that the passage from Joshua (Joshua 10: 12) in which God wills him to stop the sun in order to make the day longer concurs perfectly with a Copernican universe and not an Aristotelian–Ptolemaic one (ibid.: V, 281–8; Galilei, 1957: 181, 182, 183, 212).

Galileo's artful attempt to divide his opponents by claiming that Copernican doctrine was compatible with the Bible still did not eliminate some difficult questions. For instance, what was the sense in stating that the passage in Joshua "clearly shows us that the Aristotelian–Ptolemaic universe is not feasible" if the Bible is a text concerned solely with salvation of the soul? And, once one compares the precise language of nature to the metaphorical language of the Bible, do not natural philosophers instantly become reputable interpreters of that language? What obligation do those who read and interpret the book of nature – also written by God – have to the interpreters of the Bible when Scripture concurs with physical reality? Finally, do they not inevitably trespass that ground reserved for theologians?

Many now felt that the union of theology and natural philosophy, which for centuries had seemed to guarantee the Church's authority in matters of conscience and intellect, was forever broken. Although Lorini presented a crude and approximate version of Copernican and Galilean theory in the charges of February 7, 1615, he was clear on a few points: in the *Letter to Castelli*, which "passed through the hands of everyone," Galileo had stated that in physical matters "Scripture should be reserved to the last place;" that the interpreters of the Bible often make mistakes; that the Bible "should not concern itself in matters other than those of faith," that in the case of physical events, "scientific explanations carry greater weight than sacred or divine ones" (ibid.: XIX, 297–8). Even Cardinal Bellarmine in 1615 insisted that the conclusions reached by the Council of Trent prohibited one from expounding the Bible "contrary to the common agreement of the holy Fathers." The Church Fathers and modern writers on Genesis, Psalms, Ecclesiastes, and Joshua "all agree in expounding *ad literam* that the Sun is in the heavens and travels swiftly around the Earth, while the Earth is far from the heavens and remains motionless in the center of the world." The Church simply could not support giving to Scripture "a sense contrary to the holy Fathers and all the Greek and Latin expositors" (ibid.: XII, 171–2; Galilei, 1957: 163).

Galileo certainly struggled to separate spiritual truth from scientific fact. Yet it should be remembered that he also attempted the even thornier task of trying to find Biblical evidence for new scientific discoveries. In a letter to Piero Dini on March 23, 1614, Galileo sought to employ the very text of Psalms 18 that Dini had described as "the greatest obstacle" to the Copernican system: "God hath set his tabernacle in the Sun" (ibid.: V, 301). In commenting on this passage and pointing out meanings "congruent" with the words of the prophet, Galileo used arguments that were typically Neoplatonic and Ficinian. An "animated, tenuous, and very swift" substance that is able to penetrate all places has its principal seat in the Sun. From this place it spreads throughout all the universe and giving heat and life and making fertile all living creatures. Light, created by God on the first day, is joined to the fecund spirit in the Sun, which for this reason is at the center of the universe, and from this place they begin anew to spread through the world. The Sun is "a conjunction in the middle of the world of the heat of the stars" and, as the source of life, Galileo compared it to the heart of animals that constantly renew the vital spirits (ibid.: V, 297–305).

Galileo was trying to demonstrate that there were indeed Biblical passages that revealed the Copernican depiction of the universe. For example, there was proof that the Sun lay at the center of the universe, and that its rotation on its own axis was the force that moves the planets. Galileo believed that the Psalmist knew this basic truth of modern astronomy: that the Sun "causes all other moving bodies in the universe to revolve around it" (ibid.: V, 319).

The moment that Galileo engaged his dialectical skills to find Biblical evidence of the new cosmology he compromised the value of his overall belief in strictly separating matters of faith and science, and distinguishing between the search for "how to go to heaven" and "how the heavens go" (ibid.: V, 319; Galileo, 1957: 186).

Hypotheses and Realism

The Council of Trent concluded in 1563, and the next year Galileo was born. Once the *Professio fidei tridentinae* was issued on November 13, 1564, the boundary between heresy and orthodoxy became unyielding. In 1592, Francesco Patrizi was condemned for having claimed the existence of a single heaven, the rotation of the Earth, astral life and intelligence, and the existence of infinite space beyond the sublunar sphere. Over a ten-year period, Pope Clement VIII banned Patrizi's *Nova philosophia*, Telesio's *De rerum natura*, and the complete works of Giordano Bruno and Tommaso Campanella, initiated proceeding against Giambattista Della Porta and Cesare Cremonini, and condemned Francesco Pucci to death, imprisoned Campanella, and had Bruno burned at the stake.

On December 20, 1614, from the pulpit of Florence's Santa Maria Novella, a Dominican priest named Tommaso Caccini declared heretical Copernican theory and the ideas of any who sought to correct the Bible. He railed against "the diabolical art of mathematics" and heretical mathematicians who should be banished from every Christian nation. In early 1615, after Galileo had already been formally denounced to the Holy Office for "suspicious and reckless" statements contained in his letter to Castelli, a publication appeared in Naples entitled *Letters of the Carmelite Paolo Antonio Foscarini on the opinions of Pythagoras and Copernicus*. That book argued that the Bible and Copernicanism *were* compatible. Cardinal Bellarmine's response to the piece was an extremely significant one. Foscarini and Galileo, wrote Bellarmine, would be wise to content themselves with speaking hypothetically. To say that "*assuming* the Earth moves and the Sun stands still saves all the appearances" better than the traditional system, not only "is to speak well" but "has no danger in it." However, to affirm that the Sun *actually* is fixed at the center of the universe and it is the Earth that moves "is a very dangerous thing, not only by irritating all the theologians and scholastic philosophers, but also by injuring our holy faith and making the sacred Scripture false" (ibid.: XII, 171; Galilei, 1957: 163).

Robert Bellarmine (1542–1621) was a Jesuit priest who was made cardinal by Clement VII in 1598. He was one of the most educated and influential figures in the Church at the time. His letter to Foscarini reiterated an idea that runs through the work of Simplicius, Giovanni Filopono, and Thomas Aquinas, namely that astronomy was pure "mathematics" and pure "calculation," and a construction of hypotheses for which it was not important to decide if they corresponded to physical reality or not. This same claim had been made by Osiander in his anonymous preface to Copernicus's *De Revolutionibus*, and was a notion that Bruno rejected with great vehemence. Even Kepler had said that Ptolemy's principles were "false" while those of Copernicus "true."

Galileo was in complete agreement with Bruno and Kepler on this score. He compared pure astronomy to philosophy, and argued for a physical description rather than a hypothetical description of nature. He believed that Copernicus's inquiry had not been a means for finding calculations that conformed to observation, but rather a discussion that involved "the composition of all parts of the universe *in rerum natura*" and "the true composition of all the parts of the world." He also felt that Copernicus never believed that the Ptolemaic world system corresponded to reality: "to believe that Copernicus did not truly believe that the Earth moves, in my opinion, is not to have read him [. . .]. Furthermore, it is my belief that he was incapable of moderation insofar as the central idea of his entire doctrine was based on the mobility of the Earth and the stability of the Sun: so, we either condemn it all or leave it in its entirety" (ibid.: V, 299).

Copernicus is Condemned

December 1615 found Galileo again in Rome, and once again in the mood for argument. He elaborated on the ideas in the Castelli letter in his *Letter to Madame Christina of Lorraine*. Also in the form of a letter, to Cardinal Alessandro Orsini, he wrote a *Discourse on the tides* which he later rewrote as the fourth day in the *Dialogue on the Two Chief World Systems*. However, all his plans and false hopes were soon interrupted. On 18 February, the theologians of the Holy Office examined Copernican doctrine in the crude version supplied to them by Caccini. The Holy Office declared the first proposition – "that the Sun is the center of the world and as a result, immovable of locomotion" – to be "foolish and absurd in philosophy and substantially heretical insofar as it expressly contradicts Holy Scripture." The second proposition – "the Earth is neither at the center of the world nor immovable, but moves" – seemed to merit "from a similar philosophical perspective, the same criticism as the first; and with regard to theological verity it is at least erroneous in the faith."

Pope Paul V ordered that Galileo be *warned* to abandon Copernican doctrine. Should he refuse, he would be *ordered* (or *commanded*), in the presence of witnesses and a notary, to renounce the censured doctrine and neither defend nor teach it. The distinction between a *warning* and an *order* would prove to be of critical importance because this was the basis for the charges against him of heresy in 1633, and his subsequent condemnation on those charges. On 26 February Cardinal Bellarmine summoned Galileo. The informal record of that meeting, which was not signed by the participants and appears to be in draft form, shows that Galileo was first *warned* by the Cardinal and then immediately afterwards (*successive et incontinenti*) *ordered*, in the name of the Pontiff and the entire Commissary of the Inquisition, to "totally abandon the propositions, and neither hold, defend, nor teach them in any way (*quovis modo*) orally or in writing." When Galileo was presented with this document at the second trial, he expressed surprise and said that the terms were "completely new [to him] and never heard of before." Many historians agree that the record of that meeting does not reflect what actually happened.

On 3 March, following Galileo's appearance before Bellarmine, the Inquisition issued a decree that banned the works of Copernicus pending correction. The decree also condemned and banned Father Foscarini's work, and any book in which Copernican doctrine was upheld. And so concluded the events put in motion by Lorini's charge against Galileo, who so far had not been personally implicated. Nor had his published

works been banned. In May, after hearing about malicious insinuations and rumors that he had been forced to abjure, Galileo asked Bellarmine for a written statement. The cardinal attested that Galileo had never abjured or been punished: he had simply been notified of the Inquisition's decree that Copernican doctrine was contrary to Holy Scripture and therefore could be "neither defended nor held."

The Book of Nature

In 1623 Galileo published *The Assayer* (*Il Saggiatore*), one of the masterpieces of baroque literature; it was a biting and polemical work. The book was the offshoot of an argument with the Jesuit priest, Father Orazio Grassi, over the nature of comets. Grassi wrote the *Philosophical and Astronomical Balance* in 1619 as a response to the three lectures presented in the *Discourse on comets* by the "Galileist" Mario Guiducci. The Guiducci text was actually the work of the master himself. In both the *Discourse* and the *Assayer*, Galileo took the less-popular Aristotelian view of comets. Because parallax of the 1577 comet was much smaller than that of the moon, Tycho Brahe had correctly inferred that it lay beyond the moon. Galileo admitted that it was possible to measure distances by using parallax but rejected the application of the method to *apparent objects* (Galilei, 1890–1909: VI, 66). He classified comets as *optical phenomena*, like the sun's rays filtering through the clouds, and not *physical objects*.

In order to support his theory, Galileo attacked the astronomy of Tycho, who had believed the comets were physical bodies. Galileo, as we know, was hoping to cast the comets from the heavens and so demolish Tycho's reputation on Earth. He paid dearly for his attack on the greatest astronomer of his day: by casting himself in the role of the conservative Aristotelian, he was led to a host of inconsistencies (Shea, 1972: 88).

The Assayer, nonetheless, contains two of Galileo's most celebrated philosophical doctrines. The first stemmed from a series of reflections on the statement: "motion is the cause of heat." Galileo began by rejecting the notion that heat was an inherent quality of matter. The concept of matter or a bodily substance implied the concepts of form, relationship to other bodies, existence in time and place, motion or motionlessness, and contact or lack of it with another body. However heat, sound, odor and taste were not necessarily correlates of the concept of matter. If we were deprived of our senses, then human reason and imagination would never know that such properties existed. Though sounds, colors, odors, and tastes are considered to be objective qualities belonging to matter, they really are only "names," and when the live body is taken away, heat is reduced to a name. Galileo did not stop there. He stated that he was "inclined to believe" that what we perceive as heat is "a multitude of tiny corpuscles moving with great speed" and their "contact with our bodies is the sensation we call heat." Fire then has no other qualities than the form, multitude, motion, and penetration of fire-corpuscles and the sensation they produce.

So the physical world was laced with quantitative and measurable data, with space and "tiny particles" that move in space. Scientific knowledge can distinguish between what is objective and real in our world and what is instead subjective and produced by our senses. As Mersenne wrote in *Vérité des sciences*, the great modern abyss created between the physical universe and the world of sensory experience was far greater than the one imagined by the Skeptics.

Throughout the discussion of primary and secondary qualities, Galileo avoided using the term *atom*. He referred to *tiniest particles*, *smallest quanta*, *fire particles*, and *fire corpuscles*. At any rate, the reference was always to the smallest parts of a given substance (fire) and not to the ultimate components of matter. At the end of the *Assayer*, Galileo mentions "truly indivisible atoms." His references to atomistic–Democritean positions are especially important. In the first day of the *Discourse*, Galileo returned to the argument in the context of the phenomenon of cohesion. Simplicius condescendingly refers to "a certain ancient philosopher" and advises Salviati not to strike similar chords that "so differ from Your Lordship's well-tempered and organized mind, not only religious and pious but Catholic and holy."

The mention of particle theory in the *Assayer* did not escape the attention of the vigilant Father Grassi. In his 1626 response entitled *Ratio ponderum librae et simbellae* (*A Reckoning of Weights for the Balance*), he emphasized the similarities between the ideas of Galileo and those of Epicurus, who denied the existence of God and Divine Providence. To reduce sensory qualities to the level of subjectivity was to wage an open battle against the dogma of the Eucharist, a problem which Descartes too had to tackle. The problem lay in the fact that when the substances bread and wine are transubstantiated into the body and blood of Christ their external appearances – namely color, odor, and taste – are preserved. If, as Galileo suggested, these qualities were but "names, "then there is no need for the miraculous intervention of the Lord."

The second famous doctrine found in the *Assayer* expresses the author's belief that nature, though "deaf and unbending to our vain wishes" and producing its effects "in ways we cannot imagine," has an intrinsically harmonious order and structure, geometrical in manner: "Philosophy is written in this grand book – I mean the universe – which stands continually open to our gaze, but it cannot be understood unless one first

learns to comprehend the language and interpret the characters with which it is written. It is written in the language of mathematics, and its characters are triangles, circles, and other geometrical figures, without which it is humanly impossible to understand a single word of it; without these, one is wandering about in a dark labyrinth (Galilei, 1890–1909: VI, 232).

The book of nature is written in characters quite unlike our own alphabet, and not everyone has the ability to read it. This idea was at the heart of Galileo's firm and unyielding belief that science should not be limited to formulating hypotheses – "saving appearances" – but could actually say something about the true constitution of the parts of the universe *in rerum natura*, and could represent the physical structure of the world. Immediately following the "book of nature" passage cited above, Galileo writes that he, like Seneca, seeks "the true constitution of the universe" and describes that search as "a large request and greatly desired by me."

Galileo's meaning was perfectly understood by those who feared and despised the idea that mathematical knowledge might uncover the objective structure of the world and so compare, in some way, with divine knowledge. Cardinal Maffeo Barberini (1568–1644) – elected Pope Urban VIII in 1623 – made his position on this question clear. Given that the explanation of a natural effect may be different from the one that seems best to us, all theories should be posited as hypotheses and remain there. Galileo states the exact opposite in the *Dialogue*, and argues that mathematical knowledge may be equal to divine knowledge. Simplicius the Aristotelian is struck by the "sharpness" of Salviati's statement: "*Extensively*, that is, with regard to the multitude of intelligibles, which are infinite, the human understanding is as nothing even if it understands a thousand propositions; for a thousand in relation to infinity is zero. But taking man's understanding *intensively*, in so far as this term denotes understanding some proposition perfectly, I say that the human intellect does understand some of them perfectly, and thus in these it has as much absolute certainty as Nature itself has. Of such are the mathematical sciences alone; that is, geometry and arithmetic, in which the Divine intellect indeed knows infinitely more propositions, since it knows all. But with regard to those few which the human intellect does understand, I believe that its knowledge equals the Divine in objective certainty" (Galileo, VII: 128–9; 1953: 103).

Scholars have often pointed out that Galileo's "philosophy" reflects a convergence of different traditions. Little is achieved by trying to determine whether Galileo was a Platonist or an Aristotelian; a follower of Archimedes or an engineer who managed to generalize specific experiences (Schmitt, 1969: 128–9). Galileo was indebted to each of those traditions; his view of the world as mathematically-structured was certainly linked to Platonism; the distinction he made between compositive and resolutive method was essentially Aristotelian; the mathematization of physics was derived from Archimedes; and the crafting and use of the telescope as well as his attitude toward the mechanical arts and the Venetian Arsenal was rooted in the intellectual tradition of the "superior artisan" of the Renaissance. What was more, he even used pseudo-Dionysian light metaphysics and Hermetic and Ficinian philosophy in his brief attempt to demonstrate that certain Copernican truths were revealed in Holy Scripture.

Galileo made use of each of these traditions. Mathematical idealism combined with the legacy of the "divine Archimedes," and a form of corpuscular theory, was destined to have an explosive effect on the western world.

The *Chief Systems*

The papacy of Urban VIII appeared to be a tolerant one. In 1626, three years after he was elected Pope, Urban VIII freed Tommaso Campanella and granted him a pension. It was in this new climate that Galileo wrote the *Dialogue on the tides* [*Dialogo sopra il flusso e il reflusso del mare*]. The title subsequently struck him as overly bold, and he prudently changed it to a seemingly more neutral one: *Dialogue concerning the Two Chief Systems of the World: Ptolemaic and Copernican* [*Dialogo sopra i due massimi sistemi del mondo, tolemaico e copernicano*]. The very title excluded consideration of the so-called "third world system" formulated by Tycho Brahe, which was generally favored in Jesuit circles.

Galileo demonstrated that he was observing the Pope's insistence on a hypothetical discussion in both the preface and conclusion to the *Dialogue*. In the preface he states, "I have taken the Copernican side in the discourse, proceeding as with a pure mathematical hypothesis," and then stated that the 1616 ban had been motivated not out of scientific ignorance but for reasons of piety and religion. For this reason the Earth had been declared motionless and the opposite theory dismissed as a "mathematical whim." Captious argumentation, a cautious preface, and the final reference to the Pontiff's "angelic doctrine" would not be sufficient to ultimately save Galileo from defeat and humiliation.

The bulk of the *Dialogue* differed substantially in tone from its cautious beginning. In the work, three men have a discussion in the Venetian palazzo of the aristocrat Giovan Francesco Sagredo (1571–1620). One of the interlocutors is Sagredo himself, who plays the role of the spirited and ironic freethinker. The second interlocutor is the Florentine Filippo Salviati (1583–1614), and he plays the part of the committed

Copernican, a scientist of strong convictions and rational mind. The third participant in the discussion is the fictitious Simplicius, the Aristotelian defender of tradition. Neither naive nor ignorant, he defends an order he believes is immutable and so fears all ideas which threaten it: "the aim of this kind of philosophizing is to subvert all of natural philosophy, and wreak havoc with heaven, earth, and all the universe." Salviati also represents the audience to which the *Dialogue* is addressed. As it was written in colloquial Italian rather than Latin, its readers were not meant to be "professors" like Simplicius, but members of the court, the upper classes, the clergy, and a new intellectual class. The discussion takes place over four days: the first is devoted to the destruction of Aristotelian cosmology; the second to the daily rotation of Earth; the third to the Earth's annual rotation around the Sun; and the fourth day to a *physical proof* of the Earth's motion by way of Galileo's tidal theory.

The *Dialogue* is not a book about astronomy in the sense that it does not explain a planetary system. It aims to prove the verity of the Copernican universe and illustrate why Aristotelian cosmology and physics are untenable. It never discusses planetary motion. Galileo gives a simplified explanation of the Copernican system without eccentrics and epicycles. Unlike Copernicus, he places the Sun at the center of circular orbits, and does not bother to account for observations of planetary movement. It has been correctly pointed out that Galileo had much more faith in his mechanical philosophy of uniform circular motion than in the accuracy of the measurements to which Kepler had long and patiently devoted himself. Again, this attitude was also responsible for his total neglect of Kepler's solutions to the problems of celestial kinematics (the theory of the ellipse dates to 1609 in *Astronomia Nova*).

The first day's conversation deals with the indefensibility of the Aristotelian "construction of the world." That world had a *double structure* based on the distinction between the incorruptible celestial world and the corruptible one of elements. Aristotle himself believed that "sensible experiments were to be preferred above any argument." And so Salviati points out to Simplicius, his reasoning would be more Aristotelian if he said that the heavens were changeable because his senses tell him so than to say they were not because Aristotle said it was so. While it was once impossible to directly observe the heavens, this obstacle has been overcome by the telescope. The peaks of the moon are not the only thing that force us to reject the traditional view of the universe. Although that view seems whole and stable, it is rent at its very center by faults and contradictions: it employs for example the perfection of circular motions to prove the perfection of the celestial bodies and then uses this latter notion to prove the perfection of those same motions. The qualities of generation and degeneration, divisibility and indivisibility, alterabilty and inalterabilty "are common to all worldly things, the celestial as well as the elemental." This statement is critical for it affirms that the heavens and the earth belong to the same cosmic system and share a single science of physics: a single science of motion explains the movements of both heaven and earth. The destruction of Aristotle's cosmology necessarily destroyed his physics as well.

The Destruction of Aristotelian Cosmology

The second day's conversation is entirely devoted to a detailed rebuttal of all classical and modern arguments against the motion of the Earth. Salviati suggests that the following phenomena would occur if the Earth moved: a stone dropped from the top of a tower would not fall at its base but at a point slightly to the west; a cannon ball shot to the west would range farther out than a cannon ball shot to the east; since we feel a strong breeze when we travel on horseback, so we should feel an east wind from the Earth's great speed at all times; and the buildings and trees on the surface of the Earth should be uprooted and cast off by the centrifugal force of terrestrial movement. As Galileo privately noted, "it is remarkable that we can urinate, when we rush so swiftly after the urine: or alternately, the urine should dribble along to our knees" (Galilei, 1890–1909: III, 1, 255).

Simplicius adopts an argument that had also been used by Tycho, and suggests that a stone dropped from the top of the mast of a ship at rest will fall in a perpendicular line, while a stone dropped from the top of the mast of a moving ship will fall in an oblique line and land towards the stern of the vessel at a distance from the base of the mast. The same phenomenon, presuming the Earth moves swiftly in space, should occur when a stone is dropped from the top of a tower. Simplicius, however, unwittingly misrepresents one fact – he has never made the experiment on the ship before – and at this point Galileo makes an important claim: anyone who tries the experiment will discover the opposite of what Simplicius says will happen. However, it is actually unnecessary to conduct the experiment because "even without experiment, I am sure the effect will happen that way." Using Salviati and Sagredo as his mouthpieces, he counters the arguments of the anti-Copernicans with the principle of the relativity of motion. Heavenly movement exists exclusively for observers on the earth, and so it is not absurd to attribute daily rotation to the Earth. Because the movement produces changes in appearances, the changes occur in the same way whether one assumes the Earth moves and the Sun does not, or vice versa. Whatever motion is ascribed to the Earth, by necessity "we who participate in it remain completely

unaware of it." Salviati then suggests an experiment which alone refutes all the arguments against the motion of the Earth: imagine you are in a cabin below decks on a ship, and there are flies and butterflies in it with you, and a large bowl of water with fish in it, and a bottle that slowly drips water into another vessel beneath it, and if the ship moves at any speed "so long as the motion is uniform and not fluctuating this way and that, you will notice no change in any of the above objects, nor will you be able to tell if the ship is moving or standing still."

Galileo's assertion of relativity of motion had a significant consequence. In Aristotelian mechanics there was a crucial link between movement and the essence of objects. From this principle, not only could it be established which bodies were necessarily mobile and which were not, but it was also possible to explain why not all forms of movement were appropriate to all bodies. From the more open-ended Galilean perspective, rest and motion had nothing to do with the nature of objects; there was no such thing as an essentially mobile or immobile object, and it could not be determined *a priori* which bodies could move and which could not. The location of objects, in Aristotelian physics, was purposeful for both the object and the universe. Movement was represented as *motion* if it happened in space, as *alteration* if it related to qualities, and as *generatio* and *interitus* if it related to state of being. Motion was not a *state* but a process; a process in which things were created, realized, and completed. A body in motion changed not only in its relation to another body, but the body itself was subject to change. Galilean physics separated the motion of a body from the change that acts upon that same body. It signaled the end of both Aristotelian physics and medieval impetus theory which shared the notion that movement requires a *motive force* to produce motion and *conserve that motion* throughout. Rest and movement were now considered *continuous states* of a body. In the absence of external resistance, a force is required to stop a body in motion. Force produces not motion but acceleration. By overthrowing deeply-rooted concepts, Galileo laid open the way that would lead to the formulation of the principle of inertia.

Geometrization, Relativity, and Inertia

What textbooks describe as Galileo's principle of relativity (it is impossible to say whether a system is at rest or in uniform straight-line motion based on mechanical observations of the system itself) does not actually correspond to the theory he formulated for the purpose of demonstrating that it was impossible for an observer standing on the Earth to perceive the rotational movement of the Earth itself. Galileo enunciated a "broader" doctrine, according to which a motion "that does not fluctuate this way and that" which is common to all objects of a given system has no effect on the corresponding behavior of those objects and as a result can never be demonstrated within that system. In the famous example of the ship, Galileo used "non-fluctuating motion" to mean movement that was straight, direct, or moving along the same terrestrial meridian, and it is a distortion of the text to translate "non-fluctuating" as "rectilinear" (a term Galileo used several times elsewhere). The distinction is a significant one because the classical principle of relativity implies the concept of uniform rectilinear motion and acceptance of the principle of inertia (by which a body remains at rest or in uniform straight-line motion until an external force intervenes to change that state).

This concept is the very foundation of modern dynamics, and was never formulated by Galileo precisely because of the influence his cosmological ideas had on his physics. In the *Dialogue*, Galileo proposes a horizontal plane "sloping neither upward nor downward" upon which a moving object is indifferent to either acceleration or deceleration. Given a push, that object would continue to move the length of the plane and "if such a space were unbounded, the motion on it would likewise be boundless, that is, perpetual." The surface suggested by Galileo was not a horizontal plane tangential to the Earth's surface but a plane "which in all its parts is equally distant from the center of the Earth." Here Galileo means a spherical surface: "A surface that slopes neither up nor down would necessarily be in all its parts an equal distance from the center. However, is there any such surface in all the world? . . . none except our planet Earth, if it were given a good polishing."

Galileo's inspiration in this direction is revealed in the first day of conversation when he asserts the Aristotelian distinction between natural and unnatural motion. He claims that circular motion is *natural* and that constant rectilinear motion is *impossible*: "given that straight motion is by nature infinite, because the straight line is infinite and boundless, it is impossible for any moving object to naturally move in a straight line, that is, toward a place where it is impossible to arrive." We might imagine that straight motion perhaps occurred in the primordial chaos when the universe was still in disorder. Those straight motions, which upset the order of perfectly disposed bodies, might also "arrange in good order that which has been badly disposed." Straight motion may also serve "to move matter for the construction of a work; but once constructed, the object is to rest immovable, or if moveable, is to move only in a circle." After the most favorable and perfect placement of the parts of the universe, it is impossible for bodies to "still be naturally inclined to move in a straight line, for this would mean upsetting an object's own natural place, and causing disorder." We can then "imagine," as did Plato, that the planets in the

beginning were given straight and accelerated motion, and only later, when they achieved a certain velocity, converted straight-line motion into circular motion "whose speed thereafter was naturally uniform."

Galileo is by no means simply making a literary concession to Platonic mythology. He reprises and expands the argument later on when Salviati debates the characteristics of circular motion: "this being the motion that makes the moving body continually leave and continually arrive at the end, it alone can be essentially uniform." Acceleration occurs when a moving body approaches the point toward which it has a tendency and retardation occurs because of its reluctance to leave and go away from that point. Instead, in circular motion the moving body "is continually going away from and approaching its natural terminus, so the repulsion and the inclination are always of equal strengths in it, and this equality results in a speed which is neither retarded nor accelerated; that is, a uniformity of motion." This concept of "perpetual continuation" – not a natural feature of the infinite line – derives from this uniformity and from the fact that circular motion can be "perpetually maintained." The conclusion clearly summarizes Galileo's belief that only circular motion can naturally suit the parts of the perfectly ordered universe; straight motion is assigned by nature "to its bodies (and their parts) whenever these are to be found outside their proper places, or arranged badly."

Infinite straight-line motion is by nature impossible because nature "does not move where it is impossible to arrive." This seductive phrase expresses one of the greatest obstacles that Galileo the Copernican could not overcome. He continued to believe that circular motion was the superior motion; one which requires no explanation (in the new physics, circular motion would be explained with the help of non-inertial force). Galileo's greatest achievement and legacy – the joining of physics to astronomy – was based on the concept of the *inertial nature of circular motion*. The age-old idea of perfect celestial motion continued to hold sway over Galileo's physics.

Although it is difficult to read Galileo's *Dialogue* without "seeing" its *Newtonian potential*, it is important to not fall into the trap of attributing to a work ideas which later emerged from it. The concept of inertia in Newton's first law of motion was long in the making, and was the fruit of contributions by Descartes and Newton to Galileo's revolutionary idea. William Shea has suggested that in order to arrive at Newton's first law from Galileo's work, four steps were necessary: inertia had to be recognized as a basic law of nature, considered to imply rectilinearity, generalized from the motion of the Earth to all motion that occurs in empty space, and associated with mass as a function of the quantity of matter. Descartes managed the first three but only Newton conceived of the fourth (Shea, 1972: 9).

The Tides

In the close to twenty years that passed between writing the short treatise on the tides and the *Dialogue on Two Chief Systems*, Galileo came to believe that his theory of tidal motion and its cause was the final *physical proof* of Copernican cosmology. Galileo made the assumption that the ebb and flow of the sea was caused by motions of the Earth: daily west-to-east rotation on its axis and annual rotation around the Sun from west-to-east. The *combination of these two motions*, according to Galileo, made it so that every point on the globe moves "in a progressive and uneven way" and "changes speed sometimes by accelerating and others by decelerating." All the parts of the Earth therefore are subject to "motion that is notably different" even though no irregular or uneven motion has been assigned to the Earth."

Scholars have long emphasized that the "falseness" of Galileo's explanations (according to which tidal motion occurs only once every 24 hours) was not demonstrated by later scientific developments. Instead this explanation is hardly compatible with the progress that Galileo himself had made in physics and astronomy. After having introduced the classic principle of relativity to physics, Galileo (as Ernst Mach has noted) illicitly integrated two different frames of reference. The entire discussion on the second day of the *Dialogue* is aimed at proving that everything that happens on a moveable Earth happens just as it would on an immovable Earth. Why do only the seas reflect changes in the speed of the Earth? And why not all those objects not firmly attached to Earth? By the fourth day of *The Dialogue*, the planet Earth is no longer depicted as an inertial system (Clavelin, 1968: 480).

Galileo was trying to solve the question of the tides exclusively in terms of movement and the composition of movements; he rejected any notion of "lunar" influence and insisted unequivocally on mechanics. This insistence was paradoxically based on a strong aversion to the doctrine of influence and occult properties. Galileo was persuaded to reject as patently meaningless any tidal theory that referred to the "attraction" between the large bodies of water and the moon. He neither considered it as an alternative idea nor deemed it incoherent and false based on observable phenomena: he simply "discarded" it as the manifestation of an occult mentality. Galileo has the character of Sagredo dismiss the need for refuting similar trifles. That the Sun or the moon have anything to do with tidal motion is something "repugnant [. . .] to my intellect [. . .] which refuses to resort or succumb [. . .] to the attraction of occult qualities and similar useless fantasy." Galileo also expresses his great surprise at the fact that a man like Kepler, with such an "open and acute mind" and who believed in Copernicanism and had "at his fingertips the motions attributed to the earth" could have "given [his] assent to the moon's dominion over the waters, and to occult properties, and such puerilities."

Galileo's Tragedy

The controversy surrounding the *Assayer* had alienated Galileo from the Jesuit community. His enemies had no trouble convincing Urban VIII that Simplicius' reference in the *Dialogue* to "angelic doctrine" (according to which the causes of natural phenomena may not always be what is obvious, so it is wise to discuss them in terms of scientific hypothesis) was intentionally mocking of the Pope's authority. The Inquisitor of Florence ordered that sale of the *Dialogue* be suspended, and on October 1, 1632 Galileo was summoned to Rome by the Congregation of the Holy Office. Galileo managed to delay his departure until the first of the new year, but left on 20 January after being threatened to be taken there "bound in chains." He was quarantined because of a plague in Ponte a Centina, and after a lengthy delay finally arrived in Rome on February 13, 1633. On 12 April, a physically and morally debilitated Galileo appeared at the Holy Office. He learned that his crime was not that of having written the *Dialogue* but of having fraudulently obtained the license to publish it without informing the publisher of the 1616 injunction prohibiting the teaching and defense *quovis modo* of Copernican doctrine. Throughout the trial, Galileo maintained that he had been notified by Bellarmine and that the Cardinal himself – at Galileo's request – had later drawn up a document attesting to this. He stated that he did not recall an *injunction* issued in the presence of witnesses, and ended by stating that his true intention in writing the *Dialogue* was to prove that Copernicus' "reasoning" was invalid and inconclusive. This final phrase, made out of fear, delivered Galileo into the hands of the judges and eliminated any real possible defense. The consultors of the Inquisition had no difficulty showing that he was trying to trick the judges: "not only does he support Copernican theory with arguments never before heard, but he does so in the Italian language . . . so that his error has the best chance of catching on with the ignorant masses." Galileo moreover had attempted to step beyond the professional boundaries set for mathematicians: "The author claims to have presented a mathematical hypothesis but he gives it a physical reality, something a mathematician would never do."

In Galileo's written testimony, he states (10 May) that the terms of the 1616 document were "completely new" to him. A month later and following a second hearing the Inquisition delivered its verdict. On that same day, June 22, 1633, Galileo knelt before the cardinals of the Congregation and made a public abjuration: "I sincerely and in good faith denounce, curse, and abjure the above-stated error and heresies . . . and swear that in the future I will neither assert nor pronounce, orally or in writing, such things for which I could be again suspected, and if I know of other heretics or suspected heretics I will report them to this Holy Office" (Galilei, 1890–1909: XIX, 406–7).

The sentence was signed by seven of the ten judges and represented more than just a strike against Galileo and all his hopes and ideas. It also dealt a mortal blow to supporters of the new astronomy, within the Catholic Church itself, who believed that the Church could exercise a positive role in shaping culture. There is no doubt that the year 1633 was a critical one in the history of ideas and the history of science. Just a few months after Galileo's conviction (January 10, 1634), Descartes wrote to Mersenne – upon receiving the news – and urged him to postpone publication of his treatise on the world. He adopted the motto *bene vixit qui bene latuit*, or "he who hides well lives well," and confessed that he was tempted to burn all his papers. Ten years later, John Milton described his 1639 meeting with Galileo in *Areopagitica*: Italian intellectuals "were complaining of the enslaved state of science in their country; it had extinguished the lively Italian spirit, and for many years everything that was written was sycophantic and banal."

Galileo was sentenced to formal imprisonment. On July 1, 1633 he was transferred to Siena where he was welcomed as a friend by Archbishop Piccolomini. In December, he was allowed to return to his villa in Arcetri, outside of Florence, where he was ordered to live privately and neither "dine nor converse with" many people. His favorite daughter, Sister Maria Celeste, died on April 2, 1634 and Galileo wrote to a friend that he felt "immense sorrow and melancholy: loss of appetite, self-hate, and I continually hear calls from my beloved daughter" (ibid.: XVI, 85). At the end of 1637 Galileo began to experience loss of sight: "this earth, this universe, which I, by my remarkable discoveries and clear demonstrations had enlarged a hundred times beyond what has been believed by wise men of past ages, for me is from this time forth shrunk into so small a space as to be filled by my own sensations" (ibid.: XVII, 247).

The utterly ahistorical image which dominated nineteenth-century historiography and depicted Galileo as a freethinker and *ante litteram* positivist has been eclipsed. By the same token the many, at times clumsy, attempts to re-evaluate and justify the charges against Galileo have also been abandoned. On November 30, 1979, Pope John Paul II announced to a gathering of the Papal Academy of Sciences on the centennial of Einstein's birth, that Galileo Galilei "had suffered greatly [. . .] at the hands of the men and institutional organs of the Church" and declared

that in his opinion a "wrongful act had occurred," of the sort that Vatican II already condemned (*Acta*, 1979: 1464).

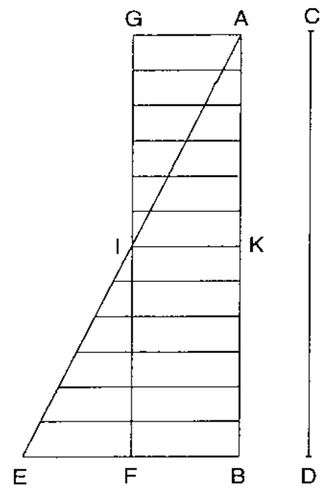
The New Physics

Studies of Galileo since the 1970s have clarified not only the importance of his early works, *De Motu* and *Mechaniche*, but also demonstrated through a detailed analysis of passages in those works that the principal problems of Galilean physics date back to the decade between 1600 and 1610. In other words, Galileo's greatest scientific work had a very long gestation period. The *Discorsi intorno a due nuove scienze/Discourses on Two New Sciences* was published in Holland in 1638, technically without his knowledge. This work featured the same three characters that appeared in the earlier *Dialogue*. On the first two days, a true discussion on the strength of materials takes place. On the third day, the problem of naturally accelerated and uniformly accelerated motion is discussed, and day four deals with the paths of projectiles. Salviati reads aloud a Latin treatise on motion that has presumably been written by his friend, Academic. The reading of the treatise is only occasionally punctuated by questions from the two interlocutors. A "fifth day" (addressing Euclid's theory of proportions) and "sixth day" (on the force of percussion) were published later, in 1774 and 1718 respectively.

A new science was born with Galileo's theory of the strength of materials: an organic body of theory was for the first time applied to civil and military engineering and the science of building. In this context, Galileo's suggestion at the beginning of the *Discourses* is very significant; that is, that "philosophizing" should take into careful consideration the work of engineers and artisans. Sagredo declares that his conversation with "extremely skilled and eloquent" mechanics helped him several times in the course of his research into "hidden and almost unforseeable" effects. Galileo emphasizes first the importance of the *scale* of a structure as a determining factor of its strength, and shows why a model is relatively stronger than the full-scale structure. Prisms and cylinders that differ in length and thickness have a resistance to fractures that is directly proportional to the cube of the diameter of their base and inversely proportional to their length. The bones of a giant would have to be disproportionately thick for their length: the size of a structure cannot grow indefinitely in either art or nature. The cohesive strength of solids and the strength of materials can be explained by their particulate or atomic composition, and either the resistance to the formation of a vacuum between those particles (demonstrated by the resistance to separation of two smooth surfaces in contact) or else the presence of a viscous substance between them. However, in studying beams and fractures, Galileo overlooked the so-called effect of compression and mistakenly believed that the strength of beams was absolute.

Philosophers and historians of science have long studied the development of Galileo's theory of uniformly accelerated motion in the third day of the *Discourses*. The formulation of that theory was the culmination of a process that grew progressively more abstracted from experiential or qualitative elements. His earlier *De Motu* shows traces of ideas such as heaviness as a natural property of bodies, the natural descent of heavy bodies, and *vis impressa* as a temporary lightness that prevails over natural gravity. The speed of fall was considered in relation to the density and weight of the falling object. In the *Discourses* Galileo instead applies a purely kinematic analysis to the question of cause: velocity is directly proportional to the space that is traveled. This initial hypothesis was later discarded in favor of velocity as directly proportional to time, a considerably less obvious idea: "If an object at rest falls with uniformly accelerated motion, the distances traversed in any given time . . . are proportional to the squares of the times elapsed."

The relationship according to which D is proportional to T^2 (Theorem II, second assumption) is derived from Theorem I according to which the time it takes an object starting from rest to traverse a given distance while moving with uniformly accelerated motion is the same as the time it takes for the same distance to be traversed by the same object moving at a constant speed equal to half of the final and greatest degree of velocity attained by the previous uniformly accelerated motion. In the figure, AB represents the time elapsed during the uniformly accelerated motion of an object starting from rest through the space CD. EB represents the final and greatest degree of velocity attained during the time period AB. We then draw AE; lines that are equidistant and parallel to EB represent the increasing velocities after the initial moment A. Make F the midpoint of EB and draw FG parallel to AB and AG parallel to FB. The area of rectangle AGFB is equal to the area of triangle AEB because GF cuts AE at the intermediate point I. Extend the parallel lines contained in triangle AEB to GIF and "the sum of all the parallels in the triangle AEB is the same as the sum of all the parallels in the rectangle ABFG." The sum of the parallels in the triangle represents the "increasing velocities" of a uniformly accelerated motion while the sum of the parallels in the rectangle represents the velocities of an object moving at a constant speed. The sum of the velocities of each motion is equal: if velocity increases uniformly from zero to EB, the distance traversed is the same as that traversed in an equal time at the uniform speed IK (which is half of speed EB). To put it in non-Galilean terms, the sum of the increasing instantaneous velocities in the accelerated motion is equal to the sum of the uniform instantaneous velocities at the mean speed IK.



Galileo did not fully identify distance with area, and his knowledge of infinitesimal calculus was insufficient to allow him to state "that the sum of an infinity of little lines, each representing a velocity, adds up to something different, a distance" (Shea, 1972). Infinitesimal calculus would prove to be the mathematical method required for dealing with continually varying quantities.

The problem which Galileo addressed in the brief Latin treatise inserted in the *Discourses* was that of finding a definition of uniformly accelerated motion that "exactly described [. . .] the kind of acceleration that nature gives to falling objects." Galileo declared that he was practically "led by the hand" to his definition because nature is served, in all its works, "by the most immediate, simple and efficient" means. A stone that falls from rest progressively gathers speed, so why not imagine that the increase in velocity occurs in the most simple and obvious way (*simplicissima et magis obvia ratione*)? There are two possibilities that meet the requirements of an increase or increment that "always occurs in the same way": velocity might be proportional to distance or to time. It has often been pointed out that the choice made by Galileo (who perceived the two options as equally simple) was tied to his erroneous demonstration of the logically contradictory nature of the alternative hypothesis.

"Through a similar uniform subdivision of time we understand that increments in velocity occur with the same simplicity." This is possible because we establish in the abstract (*mente concipientes*) that "a motion is uniformly and continuously accelerated when it receives equal increments of velocity in equal times." Sagredo observes that the definition is arbitrary – "conceived of and allowed in the abstract" – and it is doubtful whether it can be adapted to reality and physically proven. Simplicius makes the same objection at the conclusion of the lengthy demonstration. While persuaded by the validity of the demonstration, he doubts that nature really applies that sort of motion to falling bodies: "it seems to me, and to others like me, that it would be opportune in this case to gather some experiences." And so Galileo responds to this request with his famous description of a perfectly spherical, hard and smooth bronze ball that rolls down a smooth, hard, straight inclined plane. The formulation of the principle was not based on this experiment though, and Galileo states it clearly on that same page: the experiment was carried out "to demonstrate that naturally falling bodies accelerated according to the above proportions."

The Fourth Day of the *Discourses,* devoted to projectile motion, is an example of the exceptional quality of Galilean science. In these pages Galileo shows that the trajectory of a projectile is parabolic and a combination of two independent motions that *do not interfere with one another*: a forward uniform motion on the horizontal and a downward uniformly accelerated motion on the vertical. This law, which combines the principle of inertia and the law of free fall, allowed Galileo to determine speed, height, range, and quantity of motion. Galileo effectively changed the way people understood motion and introduced a radically different way of relating motion and geometry.

Galileo continued to write letters, and study and discuss problems late into his life. With the help of Viviani and his youngest disciple, Evangelista Torricelli, he was even able to recapture some of his former enthusiasm: he argued with Fortunio Liceti, followed the debate between Viviani and Torricelli, and clarified his views on Aristotelianism. In the pre-dawn hours of January 8, 1642, the now blind eyes that had been the very first to see new stars and the peaks and valleys of the moon, closed once and for all. To avoid "scandalizing good people" it was deemed unfit to construct "an august and sumptuous resting place" for his mortal remains. The Pope's nephew wrote that it would be inappropriate "to build a mausoleum for the body of one who had been convicted by the Tribunal of the Holy Inquisition and died serving his sentence."