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GALILEO
AND THE
SCIENCE DENIERS

MARIO LIVIO

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Preface

Being an astrophysicist myself, I have always been fascinated by Galileo. He was, after all, not only the founder of modern astronomy and astrophysics—the person who turned an ancient profession into a window onto the universe's deepest secrets and awe-inspiring wonders—but also a symbol of the fight for intellectual freedom.

Using a simple arrangement of lenses fixed at the two ends of a hollow cylinder, Galileo was able to revolutionize our understanding of the cosmos and of our place within it. Fast-forward four centuries, and we find a great-great-great-grandson of Galileo's telescope: the Hubble Space Telescope.

Over the decades during which I worked as a scientist with Hubble (till 2015), I was often asked what I thought gave the Hubble telescope its iconic status as one of the most recognizable projects in scientific history. I've identified at least six main reasons for Hubble's popularity. In no particular order, these are:

- The incredible images produced by the space telescope, dubbed by one journalist "the Sistine Chapel of the scientific age."

- The actual scientific discoveries to which Hubble has significantly contributed. Those range from determining the composition of the atmospheres of extrasolar planets to the astounding discovery that the cosmic expansion is accelerating.

- The drama associated with the telescope. The transformation of what was initially considered a disastrous failure—a flaw in the telescope's mirror was discovered within weeks after its launch—into a gigantic success.

- The ingenuity of scientists and engineers, coupled with the courage of astronauts, all of which helped to overcome the incredible technological challenges involved in making repairs and upgrades several hundred miles above the Earth.

- The telescope's longevity: it was launched in 1990 and is still working beautifully in 2019.

- An extraordinarily effective dissemination and outreach program, which circulates the findings to scientists, to the general public, and to educators, in an efficient, attractive, and easily accessible fashion.

Amazingly, when I carefully examined Galileo's life and work, I realized that the same key words came to mind: *images, discoveries, drama, ingenuity, courage, longevity*, and *dissemination.*

First, Galileo created breathtaking images from his observations of the lunar surface. Second, while his spectacular discoveries about the solar system and the Milky Way didn't conclusively prove that the world was Copernican, with the Earth revolving around the Sun, they all but destroyed the stability of the Earth-centered Ptolemaic universe.

Finally, the drama characterizing Galileo's life, the brilliant ingenuity he showed in his experiments in mechanics, the courage he demonstrated in defending his views, his enormous success in disseminating his findings and in making them accessible, and the fact that his ideas became the basis on which modern science has been erected, are the main characteristics that make Galileo and his story immortal.

You may wonder why I felt absolutely compelled to write another book about Galileo, when quite a few excellent biographies and analyses of his work exist already. There were three main reasons for my decision. First, I realized that very few of the known biographies were written by a research astronomer or astrophysicist. I believe, or at least hope, that someone actively engaged in astrophysical research can bring a novel perspective and fresh insights even to this seemingly overworked arena. In particular, I have attempted in this book to place Galileo's discoveries in the context of today's knowledge, ideas, and intellectual setting.

Second, and most important, I am convinced that present-day readers will be amazed to discover how relevant Galileo's story is for today. In a world of governmental antiscience attitudes with science deniers at key positions, unnecessary conflicts between science and religion, and the perception of a widening schism between the humanities and the sciences, Galileo's tale serves, first of all, as a potent reminder of the importance of freedom of thought. At the same time, Galileo's complex personality itself, grounded as it was in late-Renaissance Florence, Italy, provides a perfect example of the fact that all the achievements of the human mind are part of just *one* culture.

Finally, many of the superb, scholarly written biographies include parts that are rather abstruse or far too detailed even for educated but nonexpert readers. My goal has been to provide an accurate yet relatively short and accessible account of the life and work of this captivating man. In some sense, I am humbly attempting to follow here in Galileo's footsteps. He insisted on publishing many of his scientific findings in Italian (rather than Latin), for the benefit of every educated person rather than for a limited elite. I hope to do the same for Galileo's tale and its vitally important message.

Albert Einstein once wrote about Galileo that "he is the father of modern physics—indeed, of modern science altogether." He was echoing here philosopher and mathematician Bertrand Russell, who also called Galileo "the greatest of the founders of modern science." Einstein added that Galileo's "discovery and use of scientific reasoning" was "one of the most important achievements in the history of human thought." These two thinkers were not in the habit of offering profuse praise, but there was a solid base for these accolades. Through his pioneering, stubborn insistence that the book of nature was "written in the language of mathematics," and his successful fusion of experimentation, idealization, and quantification, Galileo literally reshaped natural history. He transformed it from being a mere collection of vague, verbal, nebulous accounts embellished by metaphors, to a magnificent opus encompassing (when the contemporary knowledge allowed it) rigorous mathematical theories. Within those theories, observations, experiments, and reasoning became the only acceptable methods for discovering facts about the world and for investigating new connections in nature. As Max Born, winner of the 1954 Nobel Prize in Physics, once put it: "The scientific attitude and methods of experimental and theoretical research have been the same through the centuries since Galileo and will remain so."

His scientific prowess notwithstanding, we should not get the impression that Galileo was the easiest or kindest person, or, for that matter, even that he was an idealistic freethinker; an explorer who accidentally wandered into theological controversy. Whereas he could indeed be extremely empathic and supportive to members of his own family, he showed blistering intolerance and belligerence, wielding his sharp pen toward scientists who disagreed with him. A number of scholars labeled Galileo a zealot, although not always a zealot for the same cause. Some said it was for Copernicanism—the scheme in which the Earth and the other planets revolve around the Sun—others claimed he was a zealot for his own self-righteousness. Still others even believed he was fighting for the Catholic Church, anxious to stop it from making a mistake of historical proportions by condemning a scientific theory that he was convinced would be proven to represent a correct description of the cosmos. In defense of his zeal, though, one would probably expect nothing less from a man who set out not only to change a worldview that had existed for centuries but also to introduce entirely new approaches to what constitutes scientific knowledge.

Undoubtedly, Galileo owes much of his scholarly fame to his spectacular discoveries with the telescope and his extremely effective dissemination of his findings. Turning this new device to the heavens instead of watching sailing ships or his neighbors, he was able to show wonders such as: there are mountains on the surface of the Moon; Jupiter has four satellites orbiting it; Venus displays a series of changing phases like the Moon; and the Milky Way is composed of a vast number of stars. But even these proverbially out-of-this-world achievements are not sufficient to explain the enormous popularity that Galileo enjoys to this very day, and the fact that he, more than almost any other scientist (with the possible exceptions of Sir Isaac Newton and Einstein), has become the perennial symbol of scientific imagination and courage. In addition, the facts that Galileo was the first to firmly establish the laws of falling bodies and the founder of the crucial concept of dynamics in physics were clearly not enough to make him the hero of the scientific revolution. What at the end distinguished Galileo from most of his contemporaries was not so much what he believed in but rather why he believed it and how he reached that belief.

Galileo based his convictions on experimental evidence (sometimes real, sometimes in the form of "thought experiments"—thinking through the consequences of a hypothesis) and theoretical contemplation, and not on authority. He was prepared to recognize and internalize that what had been trusted for centuries might be wrong. He also had the foresight to assert forcefully that the road to scientific truth is paved with patient experimentation leading to mathematical laws that weave all the observed facts into one harmonious tapestry. As such, he can definitely be regarded as one of the inventors of what we call today the scientific method: a sequence of steps that ideally (although rarely in reality) needs to be taken for the development of a new theory, or for acquiring more advanced knowledge. The Scottish empiricist philosopher David Hume gave in 1759 this personal comparison between Galileo and another famous empiricist, English philosopher and statesman Francis Bacon: "Bacon pointed out at a distance the road to true philosophy: Galileo both pointed it out to others, and made himself considerable advances in it. The Englishman was ignorant of geometry; the Florentine revived that science, excelled in it, and was the first to apply it, together with experiment, to natural philosophy."

All of Galileo's impressive insights could not have happened in a vacuum. One could perhaps even argue that the age shapes individuals more than individuals shape the age. Art historian Heinrich Wolfflin wrote once: "Even the most original talent cannot proceed beyond certain limits which are fixed for it by the date of its birth." What, then, was the backdrop against which Galileo acted and produced his unique magic?

Galileo was born in 1564, only a few days before the death of the great artist Michelangelo (and also the same year that brought the world the playwright William Shakespeare). He died in 1642, almost one year before the birth of Newton. One doesn't have to believe in the transmigration at death of the soul of one human into a new body—nobody should—to realize that the torch of culture, knowledge, and creativity is always passed from one generation to the next.

Galileo was, in many respects, an example of a product of the late Renaissance. In the words of Galileo scholar Giorgio de Santillana: "a classic type of humanist, trying to bring his culture to the awareness of the new scientific ideas." Galileo's last disciple and first biographer (or perhaps more of a hagiographer), Vincenzo Viviani, wrote about his master: "he praised the good things that had been written in philosophy and in geometry to elucidate and awaken the mind to their own order of thinking and maybe higher, *but* he said that the main entrance to the very rich treasure of material philosophy was *observations and experiments*, which through the senses as keys, could reach the most noble and inquisitive intellects." Precisely the same sentiments had been expressed by the great polymath Leonardo da Vinci about a century earlier, when he defied those who had mocked him for not being "well read," by exclaiming: "Those who study the ancients and not the works of Nature are stepsons and not sons of Nature, the mother of all good authors." Viviani further tells us that the judgment Galileo passed on various works of art was highly valued by celebrated artists such as the painter and architect Lodovico Cigoli, who was Galileo's personal friend and sometimes collaborator. Indeed, apparently in response to a request from Cigoli, Galileo wrote an essay in which he discussed the superiority of painting over sculpture. Even the famous Baroque painter Artemisia Gentileschi approached Galileo when she thought that the French noble Charles de Lorraine, 4th Duke of Guise, had not sufficiently appreciated one of her paintings. Moreover, in her painting *Judith Slaying Holofernes*, her depiction of blood squirting was in accordance with Galileo's discovery of the parabolic trajectory of projectiles.

Viviani's encomium doesn't stop there. His plaudits just go on and on. In a style very reminiscent of that of the first art historian, Giorgio Vasari, in his biographies of the greatest painters, Viviani writes that Galileo was a superb lutenist whose playing "surpassed in beauty and grace even that of his father." This particular praise appears to have been at least somewhat misplaced: while it is true that Galileo's father, Vincenzo Galilei, was a composer, lutenist, and music theorist, and that Galileo himself played the lute quite well, it was Galileo's younger brother Michelangelo who was a true lute virtuoso.

Finally, to top it all, Viviani relates that Galileo could recite at length by heart from the works of the famous Italian poets Dante Alighieri, Ludovico Ariosto, and Torquato Tasso. This was not exaggerated adulation. Galileo's favorite poem truly was Ariosto's *Orlando Furioso*, a rich, chivalric fantasy, and he devoted a serious literary work to a comparison between Ariosto and Tasso, in which he extolled

Ariosto while brutally criticizing Tasso. He once told his neighbor (and later biographer) Niccolò Gherardini that reading Tasso after Ariosto was like eating sour lemons after delicious melons. True to his Renaissance spirit, Galileo continued to be deeply interested in art and in contemporary poetry throughout his entire life, and his writings, even on scientific matters, both reflected and were informed by his literary erudition.

In addition to this splendid artistic and humanistic background, there were, of course, important scientific advances—a few genuinely revolutionary—that helped pave the way for the type of conceptual breakthroughs that Galileo was about to produce. The year 1543, in particular, witnessed the publication of not one but two books that were about to change humanity's views on both the microcosm and the macrocosm. Nicolaus Copernicus published *On the Revolutions of the Heavenly Spheres*, which proposed to demote the Earth from its central position in the solar system, and the Flemish anatomist Andreas Vesalius published *On the Fabric of the Human Body*, in which he presented a new understanding of human anatomy. Both books went against prevailing beliefs that had dominated thought since antiquity. Copernicus's book inspired others, such as philosopher Giordano Bruno and later astronomers Johannes Kepler and indeed Galileo himself, to expand the Copernican heliocentric ideas even further. Similarly, by elbowing out ancient authorities such as the Greek physician Galen, Vesalius's book incentivized William Harvey, the first anatomist to recognize the full circulation of blood in the human body, to advocate the primacy of visual evidence. Major advances happened in other branches of science as well. The English physicist William Gilbert published his influential book on the magnet in 1600, and the Swiss physician Paracelsus introduced in the sixteenth century a new perspective on diseases and toxicology.

All of these discoveries created a certain openness to science not seen in the earlier Dark Ages. Still, the intellectual outlook of even the most educated people at the end of the sixteenth century was predominantly medieval. This was about to change dramatically in terest in Euclidean geometry, which Galileo was to make creative use of. Archimedes, the greatest mathematician of antiquity, would become his role model. Among many other achievements, Archimedes formulated the law of the lever and used it capably against the Romans in his legendary war machines. "Give me a place to stand, and I will move the Earth!" he was reported to have exclaimed. Galileo was only too happy to demonstrate that most machines could, at their basic principles, be reduced to something resembling a lever. Eventually he also came to believe in the Copernican model, in which the Earth was moving even without human intervention.

More broadly, the recovery, fresh editing, and translation of texts from the classical past provided a basis for more skeptical, investigative, observational attitudes. The primacy of mathematics as key to both practical and theoretical advances was becoming apparent, and it burgeoned into Galileo's guiding light. Mathematics proved essential in areas ranging from painting (where it was used for working out vanishing points and foreshortening in perspective) to business transactions (where mathematician Luca Pacioli introduced double-entry accounting in his influential book *The Collected Knowledge of Arithmetic, Geometry, Proportion and Proportionality*). The upsurge in the numerical thinking of the time was perhaps best illustrated by an amusing anecdote involving Lord Burghley (William Cecil), the chief advisor to Queen Elizabeth I of England. According to this story, in 1555 he took the surprising step of weighing himself, his wife, his son, and all his household servants, and listing all the results.

Finally, another factor that helped to enhance the reverberations of Galileo's findings was the intense curiosity about newly discovered worlds brought about by the great explorers. Together with the geographical horizons, the span of knowledge also rolled wider starting with the last decade of the fifteenth century. Explorers such as Christopher Columbus, John Cabot, and Vasco da Gama reached the Caribbean islands, landed in North America, and found the sea route to India, respectively, just between 1492 and 1498. Then, by the 1520s, humans had circled the globe. No wonder that when the nineteenthcentury French historian Jules Michelet tried to summarize the thirst for new wisdom and humanism that characterized the Renaissance, he concluded that it encompassed "the discovery of the world and of man."

A MAN OF HIS TIME AND BEFORE HIS TIME

Galileo's journey as a scientist started in 1583, when he dropped out of medical school and began to study mathematics. By 1590, at the age of twenty-six he already had the audacity to criticize the teachings on motion of the great Greek philosopher Aristotle, according to which things moved because of a built-in impetus. About thirteen years later, following a series of ingenious experiments with inclined planes and pendulums, Galileo formulated the very first "laws of motion" concerning free fall, even though he would not publish those until 1638.

He presented his first breathtaking discoveries with the telescope in 1610, and five years later, in a famous *Letter to the Grand Duchess Christina*, expressed his risky opinion that the biblical language had to be interpreted in light of what science reveals, and not the other way around.

In spite of his personal disagreements with some orthodox church dicta, as late as May 18, 1630, Galileo was still received in Rome as an honored guest by Pope Urban VIII, and he left the city under the impression that the Pope had approved the printing of his book *Dialogue Concerning the Two Chief World Systems* after only a few minor corrections and a change of title. Overestimating the strength of his friendship with the pontiff and underestimating the fragility of the delicate psychological and political position of the Pope in that turbulent post-Reformation era, Galileo continued to believe that reason would prevail. "Facts, which at first seem improbable, will, even on scant explanation, drop the cloak which has hidden them and stand forth in naked and simple beauty," he once wrote. Imprudently neglecting his own safety, he proceeded to get the book to print, and, after a rather convoluted series of events, the book finally went to press on February 21, 1632. Whereas in the preface to the book Galileo purported to discuss the Earth's motion merely as a "mathematical caprice," the text itself had a very different flavor. In fact, Galileo taunted and derided those who still refused to accept the Copernican view in which the Earth revolved around the Sun.

Einstein said about this book:

> [It] is a mine of information for anyone interested in the cultural history of the Western world and its influence upon economic and political development. A man is here revealed who possesses the passionate will, the intelligence, and the courage to stand up as the representative of rational thinking against the host of those who, relying on the ignorance of the people and the indolence of teachers in priest's and scholar's garb, maintain and defend their positions of authority.

For Galileo, however, the publication of the *Dialogo*, as it is commonly referred to, marked the beginning of the end of his life, though not of his fame. He was tried by the inquisition in 1633, pronounced a suspected heretic, forced to recant his Copernican ideas, and eventually placed under house arrest. The *Dialogo* was put on the Vatican's *Index of Prohibited Books*, where it remained until 1835.

In 1634 Galileo suffered another devastating blow with the death of his beloved daughter Sister Maria Celeste. He still managed to write one more book, *Discourses and Mathematical Demonstrations Concerning Two New Sciences* (commonly known as *Discorsi*), which was smuggled out of Italy to Holland and published there in Leiden. The book summarized much of his life's work, from his early days in Pisa, some fifty years earlier. Although his own travel was forbidden, Galileo was allowed to have occasional visitors. One of his callers during that late period of his life was the young John Milton, of *Paradise Lost* fame.

Galileo died in 1642 at his villa in Arcetri, near Florence, after having been blind and bedridden for a while. But as we shall clearly see in this book, his science and the tale of Galileo and his times resonate strongly today. There is a striking similarity between some of the religious, social, economic, and cultural problems that a person in the seventeenth century had to struggle with, and those we encounter in the twenty-first century. Indeed, whose story is better to tell than that of Galileo if we are to shine light on current concerns such as the continuing debate about the proper realms of science and religion, the support for the teaching of creationist ideas, and the uninformed attacks on intellectualism and expertise? The blatant dismissal in some circles of the research on climate change, the mocking attitude directed at the funding of basic research, and the elimination of budgets for the arts and public radio in the United States are only a few of the manifestations of such assaults.

There are additional reasons why Galileo and his seventeenth-century world are extremely relevant for us and our cultural needs. An important one is the apparent schism between the sciences and the humanities first identified and exposed in a 1959 talk (and later a book) by British physical chemist and novelist C. P. Snow, with his coinage of the term "the Two Cultures." Snow presented his concern with great clarity: "A good many times, I have been present at gatherings of people who, by the standards of the traditional culture, are thought highly educated and who have with considerable gusto been expressing their incredulity at the illiteracy of scientists." At the same time, Snow pointed out, had he asked those very same erudite essayists to define *mass* or *acceleration*—to him, the scientific equivalent of "Can you read?"—for nine in ten of the highly educated, he might as well have been speaking a foreign language. On the whole, Snow noted that during the 1930s and onward, literary scholars started referring to themselves as "the intellectuals," thereby excluding scientists from this coterie. Some of those intellectuals even resented the penetration of scientific methods into areas not traditionally associated with the exact sciences, such as sociology, linguistics, and the arts. While surely not as extreme, their stance was not entirely dissimilar from the indignation expressed by church officials who reacted against what they regarded as Galileo's unwelcome intrusion into theology.

A few scholars argue that the problem of the two cultures is less acute today than it was when Snow gave his lecture. Others, however, claim that a proper dialogue between the two cultures is still mostly absent. Historian of science David Wootton, for example, feels that the problem has even deepened. In his book *The Invention of Science: A New History of the Scientific Revolution*, Wootton writes: "History of science, far from serving as a bridge between the arts and sciences, nowadays offers the scientists a picture of themselves that most of them cannot recognize."

In 1991 author and literary agent John Brockman introduced the concept of a "third culture," in online conversation and later in a book with that title. According to Brockman, the third culture "consists of those scientists and other thinkers in the empirical world who, through their work and expository writing, are taking the place of the traditional intellectuals in rendering visible the deeper meaning of our lives, redefining who and what we are." As we shall see in this book, four hundred years ago, Galileo would have secured himself a place of honor in the third culture.

The border between art and science was largely blurred during the Renaissance, with artists such as Leonardo da Vinci, Piero della Francesca, Albrecht Dürer, and Filippo Brunelleschi having been involved in serious scientific research or in mathematics. Consequently, Galileo himself embodied an integration of the humanities and the sciences that can serve as a model to be examined, even if not easily emulated today. Consider, for instance, that at age twenty-four, he presented two lectures on the topic of "On the Shape, Location, and Size of Dante's *Inferno*," or the fact that even Galileo's science involved, to a great extent, the visual arts. For example, in his book *The Sidereal Messenger* (*Sidereus Nuncius*), a booklet of sixty pages that was rushed to print in 1610, he tells his scientific story of the

Chapter 2

A Humanist Scientist

Galileo Galilei was born in Pisa on February 15 or 16, 1564. His mother, Giulia Ammannati, was an educated, if prickly, difficult, and bitter woman from Pescia, whose family was involved in the wool and clothing business. His father, Vincenzo, was a Florentine musician and music theorist from a family with noble roots, but who had rather unimpressive financial means. Even then, musicians struggled to support themselves and their families on their music alone, so Vincenzo apparently also became a part-time cloth merchant. The couple married in 1563, and, following Galileo, had two more sons and three or, according to some, four daughters. Of these, only Galileo's younger brother, Michelangelo, and the two sisters Livia and Virginia played significant roles in Galileo's life.

Genetics are inescapable. In Galileo's case, he may have inherited at least some of his rebellious nature, self-righteousness, and distrust of authority from his father, and his selfishness, jealousy, and anxiety from his mother. Vincenzo Galilei objected vehemently to the musical theory promoted by his own teacher, Gioseffo Zarlino. A music theorist from the old school, Zarlino was a strong advocate of a tradition that dated all the way back to the ancient Pythagoreans, according to which all string-generated sounds that are pleasant to our ears (such as the octave or the fifth) are the result of plucking identical strings, with lengths that are in ratios of integer numbers such as 1:2, 2:3, 3:4, and so on. It was the uncompromising clinging to this scheme that produced the old joke that Renaissance musicians spent half their time tuning their instruments and the other half playing out of tune.

Vincenzo, on the other hand, maintained that adhering to this conservative numerology was arbitrary and that other criteria, equally valid if not better, could be adopted. In simple terms, Galileo's father argued that musical consonance is determined by the musician's ear rather than by his or her arithmetical capabilities. By insisting on freeing music from Pythagoras, Vincenzo opened the door for the modern "equally tempered system" popularized later by Johann Sebastian Bach. Through a series of experiments with strings of different materials and of varying tensions, he showed, for example, that strings of different tensions could produce the octave at a length ratio different from the canonical 2:1 (which was used when the tension was held constant). Almost prophetically—or rather, probably having an influence on his son—Vincenzo entitled one of his books on the subject *Dialogue on Ancient and Modern Music*, and another *Discourse Concerning the Work of Messer Gioseffo Zarlino of Chioggia.* Years later, two of Galileo's most important books would be entitled *Dialogue Concerning the Two Chief World Systems* and *Discourses and Mathematical Demonstrations Concerning Two New Sciences.* One sentence in particular in Vincenzo's fictional dialogue on music precisely captured the credo that Galileo was about to espouse later in life. The two interlocutors agree from the outset that they should invariably "set aside . . . not only authority, but also reasoning that seems plausible but is contradictory to the perception of truth."

The young Galileo probably helped his father in the experiments with the strings, and in the process, he might have started to realize the importance of the evidence-based approach to science. This could have been the first step in Galileo becoming a firm believer in the concept that in trying to find descriptions of natural phenomena, one needs, as he later expressed it: "to seek out and clarify the definition that best agrees with that which nature employs." Having to perform a series of experiments with weights hung on strings (to vary the tension), may have also planted in his mind the seeds of the idea of using pendulums to measure time.

Vincenzo was not only a talented lutenist, and his interests went beyond his particular objections to contrapuntal polyphony. Besides being an active member of the Florentine Camerata—a group of cultured Florentine intelligentsia interested in music and literature—he was educated in the classical languages and in mathematics. In short, not just in terms of the period of time during which he happened to live, Vincenzo was quite what we would call today a Renaissance man.

Having grown up in that milieu, Galileo was about to follow in his father's intellectual footsteps—although not in the direction of music, even though he often played second lute with Vincenzo. At the same time, having also witnessed his father's idealistic ambitions being frustrated by harsh reality, especially economically, may have instilled in Galileo a stubborn, tenacious will to succeed.

Galileo's relationship with his mother was rather more problematic. Even Galileo's brother Michelangelo described her as an absolutely "terrible" woman. Yet, in spite of numerous unpleasant incidents that included Giulia spying on Galileo and attempting to steal a few of his telescope lenses in order to give them to her son-in-law, he did his best in later years to attend to her ever-growing pecuniary needs.

Galileo's father returned from Pisa to Florence when Galileo was about ten. Lack of space in the home of a financially strapped family, in which the number of children was rapidly increasing, may have been one of the reasons for leaving Galileo in Pisa for a while, to live with his mother's relative Muzio Tedaldi. His primary education at that stage was in what we normally refer to today as the liberal arts: Latin, poetry, and music. Both Galileo's first biographer, Viviani, and Galileo's neighbor and second biographer, Niccolò Gherardini, tell us that Galileo rapidly surpassed the level at which his teacher was able to help him and that he continued his schooling through reading classical authors by himself.

At age eleven, he was sent to the monastery at Vallombrosa, in the serene atmosphere of which he studied logic, rhetoric, and grammar. He was also exposed to the visual arts by virtue of observing the work of artists in residence at the monastery. At that impressionable age, he must have been inspired by the abbot of Vallombrosa, who was apparently a polymath with knowledge in fields ranging from mathematics, to astrology, to theology, as well as in "all the other sound arts and sciences."

While there is no doubt that Galileo found the intellectual and spiritual ambience at the monastery appealing, we don't know with certainty whether he truly intended to become a novice of the order of Camaldolese monks. Be that as it may, however, Vincenzo certainly had different plans for Galileo. Partly wanting perhaps to revive his family's glorious past, which included a great-grandfather who had been a famous Florentine medical doctor, but at the same time striving to ensure Galileo's economic future, Vincenzo enrolled his son as a medical student at the University of Pisa in September 1580.

Unfortunately, medicine, which at the time was being taught based primarily on the teachings of the celebrated anatomist from ancient Greece Galen of Pergamum and which was filled with rigid rules and superstitions, bored Galileo. He did not feel that he should "give himself up . . . almost blindly" to the assertions and opinions of archaic writers. However, something good did come out of his first years at Pisa: he met the Tuscan court mathematician Ostilio Ricci. After listening to Ricci's lectures on Euclidean geometry, Galileo was bewitched. In fact, according to Viviani, even earlier, "the great talent and delight that he had . . . in painting, perspective, and music, hearing his father frequently say that such things had their origin in geometry, moved in him a desire to try it." Consequently, he started to devote all of his time to studying Euclid on his own, while totally neglecting medicine.

More than three centuries later, Einstein would be quoted as saying: "If Euclid failed to kindle your youthful enthusiasm, then you were not born to be a scientific thinker." Galileo passed this particular "test" with flying colors. Moreover, envisaging mathematics as his vocation, he introduced Ricci to his father in the summer of 1583, hoping that the mathematician would convince Vincenzo that this was the right choice. Ricci explained to Vincenzo that mathematics was the topic Galileo was truly passionate about, and expressed his willingness to be the young man's instructor. Vincenzo, who was a fairly good mathematician himself, did not object in principle, but he had the legitimate fatherly concern that Galileo would not find a job in mathematics. After all, he himself had already experienced what it meant to have the not particularly remunerative profession of a musician. Therefore, he insisted that Galileo complete his studies of medicine first, threatening that he would close his purse if Galileo refused. Fortunately for the history of science, the father and son eventually reached a compromise: Galileo could continue his studies of mathematics for one more year, with his father's support, after which he would take on the obligation of sustaining himself.

Ricci introduced Galileo to the works of Archimedes, whose genius in applying mathematics to physics and to real-life engineering problems was to motivate Galileo and permeate his entire scientific work. Ricci's own professor, mathematician Niccolò Tartaglia, was the scholar who published a few of Archimedes's works in Latin, and he had also produced an authoritative Italian translation of Euclid's masterwork *The Elements.* Not surprisingly, two of Galileo's very first treatises—one that addressed the problem of finding the center-of-mass of a system of weights, and the other on the conditions under which bodies float in water—were both on topics in which Archimedes had shown great interest. Galileo's second biographer, Gherardini, cited Galileo as saying: "One could travel securely without hindrance through heaven and earth, if one only did not lose sight of the teachings of Archimedes." The ironic net result of this entire sequence of events in the young man's life, however, was that Galileo—one of the challenge the great Aristotle on topics related to motion, even though the necessary mathematical tools to treat such variables as velocity and acceleration did not exist yet. (Calculus, which allowed for the proper definitions of velocity and acceleration as *rates* of changes, was formulated by Newton and Gottfried Leibniz only in the mid-seventeenth century.)

The second interesting point was that Galileo did reach the tentative conclusion that irrespective of their weight, falling bodies made of the same material move with the same speed in a given medium. In later years, this was going to be part of one of his major discoveries in mechanics.

Given the drama associated with Galileo's name and his acceptance of Copernicanism, it is also intriguing to discover that in a separate manuscript, *Treatise on the Sphere, or Cosmography*—probably written in the late 1580s and most likely intended primarily for his private teachings—Galileo fully adopted the old Ptolemaic geocentric system in which the Sun, the Moon, and all the planets revolved around the Earth in circular orbits. This was about to change drastically in the years to come.

In an attempt to beef up his still unremarkable résumé, Galileo paid a visit in 1587 to the foremost mathematician of the Jesuit order in Rome: Christopher Clavius. Clavius, who became a full member of the order in 1575, had been teaching the mathematical subjects at Rome's prestigious Collegio Romano since 1564. In 1582 he was the senior mathematician on the commission that instituted the Gregorian calendar. Galileo set his eyes on one position in particular: a chair of mathematics had opened up at the University of Bologna, the oldest university in the Western world, and one that boasted distinguished alumni such as Nicolaus Copernicus and humanist and architect Leon Battista Alberti. Hoping to secure Clavius's recommendation, Galileo left with him a few of his original works on finding the center of gravity of various solids—a popular topic among Jesuit mathematicians at the time.

At about the same time, Galileo also proved an interesting theorem that generated some buzz. He showed that if you take a series of weights of, say, 1 libra (an ancient unit of weight equal to approximately 11.5 ounces), 2 libras, 3 libras, 4 libras, and 5 libras, and hang them at equal spaces along a balance arm, then the center of gravity (the point around which the arm is in equilibrium) divides the length of the balance arm precisely in a two-to-one ratio. While this little theorem gained Galileo some recognition in places ranging from Padua and Rome to universities in Belgium, the chair at Bologna was still given to Giovanni Antonio Magini, an established astronomer, cartographer (mapmaker), and mathematician from Padua.

This failure must have been a stinging blow to the young and ambitious Galileo, but its impact was soon softened by a remarkable honor conferred upon him. In 1588 the consul of the Florentine Academy, Baccio Valori, invited Galileo to deliver two lectures to the academy on the geography and architecture of Dante's *Inferno* (hell) in his masterpiece *The Divine Comedy.*

In this monumental poetic work (running more than fourteen thousand lines), Dante tells the story of a poet's imaginative journey through the afterlife, drawing inspiration from a wide range of philosophies. After an epic tour through the Inferno and Purgatory to Paradise, the poet finally reaches that "love that moves the Sun and other stars."

The invitation to present the lectures demonstrated the Academy's respect not only for Galileo's mathematical skills but also for his literary scholarship. Galileo was undoubtedly delighted to receive this request for two main reasons. First, mapping Dante's disorienting description of hell in *The Divine Comedy* gave Galileo his first opportunity to attempt to build a bridge between a literary magnum opus and scientific reasoning. In later years, an important part of what was to become Galileo's continuous philosophy and ultimate legacy was the demonstration that science is an integral part of culture, and that it can enhance, rather than diminish, even the poetic experience. As a means to this goal, he went against the long-standing tradition of writing science in Latin and wrote instead in Italian. Working in the other direction, in his extensive scientific writing, Galileo drew from his literary resources to convey ideas and associations in a colorful, stimulating fashion.

Second, Galileo shrewdly recognized the importance of these lectures for his personal career. He was fundamentally asked to act as an arbiter between two contradictory commentaries and views on the location, structure, and dimensions of the *Inferno*, offered by two interpreters of Dante's work. One was the beloved Florentine architect and mathematician Antonio Manetti, biographer of the famous architect Filippo Brunelleschi. The other was the intellectual Alessandro Vellutello of Lucca. Vellutello argued that Manetti's amphitheater-like edifice could not be stable, and he offered an alternative model in which hell occupied a much smaller volume around the Earth's center. Much more than a purely highbrow dispute was at stake. Florence had suffered a humiliating military disaster at Lucca in 1430. After an unsuccessful besieging of that city, Brunelleschi, acting that time as an army engineer, came up with the idea of diverting the river Serchio, so as to surround Lucca with a lake and force it to surrender. The plan backfired cataclysmically when a dike failed, and the river flooded the camp of the Florentine army instead. This painful historical memory was surely on the minds of the members of the Florentine Academy when they asked Galileo to demonstrate that Manetti "had been slandered by Vellutello." Moreover, Vellutello's commentary represented a disowning of Manetti's authority—and, by association, the Florentine Academy's—in the interpretation of Dante. In other words, Galileo was entrusted with saving the academy's prestige, and he realized that by handing Manetti a victory over Vellutello, he could be regarded as a champion of Florentine pride.

Galileo started his first lecture with a direct reference to astronomical observations (probably having in mind the fact that most of the positions he was seeking at the time were in mathematics and astronomy) but emphasizing that deciphering the architecture of hell would require theoretical considerations. He then swiftly moved on to describing Manetti's interpretation, using the same analytical skills that would become his trademark in all of his scientific investigations. The dark scenery of Dante's hell occupied a cone-shaped portion of the Earth, with Jerusalem at the center of the cone's dome-shaped base and the cone's vertex being fixed at the Earth's center (Figure 2.1 shows Botticelli's depiction). Contrary to Vellutello's claim that Manetti's structure occupied a full one-sixth of the Earth's volume, Galileo used the geometry of solids he had learned from reading the works of Archimedes to demonstrate that, in fact, it filled less than seven-hundredths of the bulk—in his words: "less than one of the 14 parts of the whole aggregate." He then methodically proceeded to tear apart Vellutello's model by showing that not only would parts of his proposed architecture have collapsed under their own weight, but also that the design did not even agree with Dante's chilling description of the descent to hell. In contrast, Galileo argued that in Manetti's construction, "its thickness is sufficient . . . to sustain it." Galileo

Figure 2.1. Sandro Botticelli's *Chart of Hell*, based on Dante's *Inferno.*

finished his *Inferno* lectures by thanking the academy, to which he felt "most obligated," wisely adding that he thought he had demonstrated "how much subtler is the invention of Manetti."

Unfortunately, in perhaps wishing too much to please his audience, Galileo fell into his own trap. He didn't realize that Manetti's architectural structure was also prone to catastrophic collapse (not that any of his listeners noticed). Galileo may have discovered his blunder shortly after delivering the *Inferno* lectures, since he stopped referring to them for many years, and his biographer, Viviani, never even mentioned the lectures, despite having lived in Galileo's house during the master's last years.

Only in his last book, on the *Two New Sciences*, did Galileo return to the interesting problem of the strength and stability of constructions when they are scaled up in size. The key insight he had gained by then was that whereas the volume (and therefore the weight) increases a thousandfold when the size is blown up to be ten times larger, the resistance to cracking (which happens along two-dimensional surfaces) increases only a hundredfold, and therefore falls behind the increase in the weight. Galileo wrote in *Two New Sciences*: "The larger machine, made of the same material and the same proportions as the smaller one, in all other conditions will react with the right symmetry to the smaller one, except for its strength and its resistance against violent invasions; the bigger the ship, the weaker it will be." Then, most likely alluding to his *Inferno* mishap, he noted that "some time ago" he also had made a mistake when estimating the strength of scaled-up objects. Perhaps the most remarkable point about Galileo's flawed *Inferno* incident was the fact that even many years after having delivered a scientific talk about a poetic work, Galileo felt compelled to revisit his conclusions, revise his old ideas based on newly acquired acuity, and publish the new, correct results in an entirely different context for the problem.

Galileo was indeed a Renaissance man, but one may wonder whether in our age of narrowly focused specialization and career-driven attitudes such people still exist, and whether individuals who

Chapter 3

A Leaning Tower and Inclined Planes

Galileo's first appointment as a professor and chair of mathematics at Pisa lasted only from 1589 till 1592, yet one particular story associated with that period has generated an iconic image of Galileo. It is a picture of him dressed in his imposing academic gown, dropping balls of different weights from the top of the leaning tower of Pisa.

The original tale comes from Viviani, who in 1657 put together what he described as his recollections from a conversation he had with Galileo in the latter's final years:

> A great many conclusions of Aristotle himself on the subject of motion were shown by him [Galileo] to be false which up to that time had been held as most clear and indubitable, as (among others) that speeds of unequal weights of the same material moving through the same medium did not at all preserve the ratio of their heaviness assigned to them by Aristotle, but rather, these all moved with equal speeds, he [Galileo] showing this by repeated experiments made from the height of the leaning tower of Pisa in the presence of other professors and all the students.

In other words, contrary to the view held by all Aristotelians that the heavier the ball, the faster it would fall, Viviani claimed that by dropping balls from the Leaning Tower (sometime between 1589 and 1592), Galileo had demonstrated that two balls of the same material but of different weights hit the ground simultaneously.

As if this story wasn't dramatic enough, later biographers and historians just kept adding more details that weren't included in Viviani's original account or in any other contemporary sources. For example, British astronomer and popularizer of science Richard Arman Gregory wrote in 1917 that members of the University of Pisa assembled at the foot of the Leaning Tower "one morning in the year 1591," even though Viviani never mentioned the precise year or the time of day. Gregory also added that one ball was "weighing a hundred times more than the other"—again a detail not given by Viviani. Author Francis Jameson Rowbotham, who wrote about the lives of great scientists, great musicians, great authors, and great artists, added in his 1918 vivid description that Galileo "invited the whole University to witness the experiment."

Others were equally inventive. Physicist and historian of science William Cecil Dampier Whetham tells us in 1929 that Galileo dropped "a ten-pound weight and a one-pound weight together," repeating the same values of weights that had been mentioned in an earlier biography by Galileo scholar John Joseph Fahie. All of these science historians and others took the tower story to mark a turning point in the history of science: a change from reliance on authority to experimental physics. The event had become so famous that in a fresco painted in 1816 by Tuscan painter Luigi Catani, Galileo is shown performing the experiment even in the presence of the grand duke. But did this demonstration really take place?

Most present-day historians of science think that it probably did not. The skepticism stems partly from Viviani's known tendency for ahistorical embellishments, partly from his occasional errors in recording the chronology of events, and perhaps mostly from the fact that Galileo himself never mentions this very specific experiment in his extensive writings, nor does it appear in any other contemporary documents. In particular, philosopher Jacopo Mazzoni, who was a professor at Pisa and a friend of Galileo, published a book in 1597, in which, while he generally supported Galileo's ideas on motion, he never mentioned an experiment by Galileo at the tower of Pisa. Similarly, Giorgio Coresio, a lecturer at Pisa who described in 1612 experiments that involved dropping objects from the top of the Tower of Pisa didn't attribute any of those to Galileo. We should note that Coresio made the strange claim that the experiments "confirmed the statement of Aristotle . . . that the larger body of the same material moves more swiftly than the smaller, and in proportion as the weight increases so does the velocity." This statement becomes especially puzzling when we realize that already in 1544, historian Benedetto Varchi mentioned experiments that had shown Aristotle's prediction to be wrong.

Galileo was seventy-five when Viviani came to live in his house; Viviani was eighteen, so embellishments could have come from both sides. I would argue, however, that from the perspective of appreciating Galileo's science, it is really not very important whether he performed this particular demonstration or not. The fact remains that during his years at Pisa, Galileo embarked on serious experimentation with free-falling bodies. This stands up irrespective of whether he dropped balls from the Leaning Tower or not. In Pisa, he also started composing a treatise analyzing various aspects of motion. This monograph, *De Motu Antiquiora* (*The Older Writings on Motion*), was published only in 1687, after Galileo's death, but its contents traces the development of his early ideas, and definitely puts Galileo (already during his early Pisan years) at the forefront of both experimental and theoretical investigations of motion in general, and of free-falling bodies in particular. In *De Motu* (*On Motion*) Galileo stated that he had confirmed by repeated experiments (without mentioning the Leaning Tower) that when two objects are dropped from a high place, the lighter one moves faster at first, but then the heavier object overtakes it and reaches the bottom first. This peculiar result has been shown by later experiments to be probably due to a nonsimultaneous release of the two objects. Basically, experiments have demonstrated that when each ball is held in one hand, the hand holding the heavier object becomes more tired, and it has to clasp the object with more force, resulting in a delayed release. Incidentally, the Flemish physicist Simon Stevin of Bruges dropped two balls of lead, one ten times the weight of the other, "from a point about 30 feet high," some years before Galileo's supposed Leaning Tower demonstration, and he published his results ("they landed so evenly that there seemed to be only one thump") in 1586.

De Motu marked the beginning of Galileo's serious criticism of Aristotle, and it formed the basis for his subsequent experiments with balls rolling down inclined planes. It also demonstrated that science sometimes progresses incrementally rather than as a result of revolutions. While Galileo's ideas about free-falling bodies departed significantly from those of earlier natural philosophers, at their initial stages they still did not quite square with the results of his experiments. The concepts inherited from Aristotle suggested that bodies fall at a constant speed, which is determined by the weight of the body and the resistance of the medium. To many, the fact that Aristotle had said so was sufficient to accept this as the truth. In *De Motu*, Galileo held that falling bodies accelerate (speed up), but only initially, and then they settle down to a constant proper speed, which is determined by the relative densities of the body and the medium. That is, he suggested that a ball made of lead moves faster [in Galileo's words, "far out in front"] than one made of wood, but that two balls of lead fall with the same speed, no matter how much they weigh. This was a step in the right direction, but not quite correct. For instance, Galileo realized that this description did not agree with the fact that free fall appeared to be continuously accelerating, but he thought that the speeding up itself might be gradually decreasing, eventually approaching a constant speed.

Only in his later book *Discourses and Mathematical Demonstrations Concerning Two New Sciences* (*Discorsi*) published in 1638, did Galileo arrive at a correct theory of free fall, according to which, in a vacuum, all bodies, irrespective of their weights or densities, *uniformly accelerate in precisely the same way.* Galileo put this explanation in the mouth of Salviati, Galileo's alter ego in the fictional dialogue in *Discorsi*: "Aristotle says, 'A hundred-pound iron ball falling from the height of a hundred braccia hits the ground before one of just one pound has descended a single braccio.' I say that they arrive at the same time." This crucial realization of Galileo's—the result of a vigorous experimental effort—was an essential prerequisite to Newton's theory of gravitation.

In modern times, in 1971 Apollo 15 astronaut David Scott dropped from the same height a hammer weighing 2.91 pounds and a feather weighing 0.066 pounds on the Moon (where there is virtually no air resistance), and the two objects struck the lunar surface simultaneously, just as Galileo had concluded centuries earlier.

Another problem with *De Motu* was that Galileo's early measurements, particularly of time, were still not sufficiently precise to allow for any definitive conclusions. He nevertheless had the foresight to make the following remark:

> When a person has discovered the truth about something and has established it with great effort, then, on viewing his discoveries more carefully, he often realizes that what he has taken such pains to find might have been perceived with the greatest ease. For truth has the property that it is not so deeply concealed as many have thought; indeed, its traces shine brightly in various places, and there are many paths by which it is approached.

In later years, questions such as "What is truth?" and "How is truth shown?" (especially in scientific theories) were to become essential in Galileo's life. These same questions have become perhaps even more critical today, when even indisputable facts are sometimes labeled "fake news." It is certainly true that, at their inception, the sciences were not immune to false beliefs, since they were sometimes connected to fictitious fields such as alchemy and astrology. This was unglamorous status of mathematics at the time. By comparison, philosopher Jacopo Mazzoni was making more than ten times that amount at the same university. The death of Galileo's father in 1591 put an enormous financial burden on him, since he was the eldest son. He therefore sought, and fortunately obtained, an appointment at the University of Padua in 1592, where his salary was tripled. That prestigious chair had been vacant since the death of renowned mathematician Giuseppe Moletti in 1588, and university officials were rather picky in choosing a successor. Galileo's winning the position was aided greatly by the strong support of Neapolitan humanist Giovanni Vincenzo Pinelli, whose library in Padua—at the time the largest in Italy—functioned as an intellectual center, and whose strong recommendation carried enormous weight. Pinelli opened his library for Galileo, and it was there that he gained access to unpublished manuscripts and lecture notes on optics, all of which were to become helpful in Galileo's later work with the telescope.

Galileo would later describe his years in Padua—the city about which Shakespeare wrote: "fair Padua, nursery of the arts"—as the best time of his life. This was no doubt due largely to the freedom of thought and lively exchanges of information enjoyed by all scholars in the Venetian Republic, of which Padua was a part. These were also the years in which Galileo "converted" to Copernicanism.

PADUAN MECHANICS

Every researcher today knows that one cannot expect experimental results to demonstrate *precisely* any quantitative prediction. Statistical and systematic uncertainties (a range of values likely to enclose the real value)—creep into every measurement, making it sometimes difficult to even discern existing patterns at first glance. This concept runs contrary to the ancient Greeks' emphasis on very precise pronouncements. Living in a period in which no accurate measurements of time were possible, Galileo found the study of motion quite chal-