History of Physics

Alessandro De Angelis

Galileo Galilei's "Two New Sciences"

for Modern Readers

Springer

History of Physics

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Alessandro De Angelis
Dipartimento di Fisica e Astronomia
"Galileo Galilei"
Università di Padova
Padova, Italy

ISSN 2730-7549 ISSN 2730-7557 (electronic)
History of Physics
ISBN 978-3-030-71951-7 ISBN 978-3-030-71952-4 (eBook)
https://doi.org/10.1007/978-3-030-71952-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

To the memory of Antonio Favaro

All knowledge of reality starts from experience and ends in it. Propositions arrived at by purely logical means are completely empty as regards reality. Because Galileo saw this, and particularly because he drummed it into the scientific world, he is the father of modern physics—indeed, of modern science altogether.

Albert Einstein, "On the method of theoretical physics", Oxford, 1933

Preface by Ugo Amaldi

With great surprise I received in July 2019 from Alessandro De Angelis the draft of a modern version of Galileo's *Discourses and mathematical demonstrations related to two new sciences*; De Angelis asked me for an opinion on his work. A few sentences in his cover letter were saying: "Although the title contains the word 'mathematics', Galilei, like Newton, manipulated algebraic formulas only in a limited way and instead used geometry for his proofs. Notational mathematics, such as $F = ma$, and analytic geometry, were being developed at the same time as Galileo, and he did not use them. Furthermore, Galilei wrote in a somewhat 'baroque' way (excuse me for the expression) and his writings are difficult to understand. Understanding Galilei requires some knowledge of the classic Latin and Greek literature and a passion for physics, qualities not so common to find together. However, many could be enriched by knowing the art, intelligence, and beauty of his arguments, and by sharing the wonder that can often be encountered between the lines of his writings. For this reason, I decided to translate Galilei's *Discourses and mathematical demonstrations* in modern language and algebraic formulas to make him current and understandable by those who I imagine are 'modern' learned readers: curious, passionate about science, but unfortunately with little time to deepen the lexical, historical, and philosophical antiquities."

I was immediately reminded of an episode, unique in my life, happened thirty years earlier, in 1990, when for about ten years I had been the spokesperson of the international collaboration DELPHI, made up of about five hundred physicists from about twenty different countries. A year earlier, we had finished building a particle detector for CERN's electron-positron collider LEP and, having collected a lot of data, we were publishing our first scientific papers. The young Alessandro was a graduate student at the University of Padua, one of the thirty graduate students of the collaboration, with whom I had talked about physics, sometimes finding him highly educated for his age and open to new ideas. Entering my office with shyness, he placed on my desk a scientific note ready for publication, with all the necessary bibliographic indications, on a subject different from all those on which hundreds of much older and more experienced collaborators worked; when I read it I was struck by the clarity of the exposition and the completeness of the data analysis. That communication on the phenomenon of "intermittency," soon published by a prestigious magazine, is still one of the most referenced and interesting papers published by DELPHI.

A few years later I resigned from DELPHI spokesperson to deal with applications of hadron accelerators to cancer therapy and Alessandro left particle physics to work in astroparticle physics so that we did not have many opportunities to meet, even if I could follow in scientific journals the interesting results obtained with the MAGIC telescope at the international observatory of La Palma, a telescope of which he was one of the inventors. Later, in 2015, I found on my desk at CERN a 700-page volume, written with Mário Pimenta—who had been as well a graduate student in the DELPHI group in Lisbon many years earlier—and published by Springer under the title *Introduction to Particle and Astroparticle Physics.* Reading the last chapter, dedicated to *Astrobiology and the Relation of Fundamental Physics to Life,* was in particular a great intellectual pleasure. I was once again amazed by the quality and originality of his work.

When I went through the first version of the present book I experienced the same feelings of astonishment and intellectual pleasure. As he told me by phone shortly after his first email, De Angelis had been passionate about *Discourses and mathematical demonstrations* since high school, when on the sidelines he noted the translation into an algebraic language of the proofs based on geometry: "For me to demonstrate geometrically is a bit like looking at things from above, synthetically; demonstrating algebraically is like looking at them from below, analytically."

The last book published by Galilei, *Discourses and mathematical demonstrations...* is, in a sense, his first one, because from the very beginning of his teaching in Pisa Galilei started to collect, also with some help from his students, his notes on mechanics. Throughout his life, and in the Paduan period in particular, he continued filling notebooks on this subject, until he finished this book at a late age in 1638. The Preface to the *Discourses...* reveals the concern of the publisher Lodewijk Elzevir—that Galilei found in Holland with much effort—who feared it would not be taken into sufficient consideration since Galileo was famous for the publication, in 1632, of the *Dialogue concerning the two chief world systems,* and then writes (in the paraphrase/translation by De Angelis): "The divine and natural gifts of Galilei are clear in the present work where he shows to have discovered, through many labors and vigils, two entirely new sciences, and to have demonstrated them in a conclusive, i.e., mathematical, way. What is even more remarkable in this work is the fact that one of the two sciences deals with a very old subject, perhaps the most important in nature: [..] I refer here to motion. [..] The other science which he has also developed from its very foundations deals with the resistance which solid bodies offer to fracture by external forces, a subject of great utility, especially in the sciences and in the art of construction. [,,,] This book treats for the first time these two sciences and is full of conclusions to which, over time, others will be added by new thinkers. Moreover, through a large number of very clear demonstrations, the author paves the way for many new theorems that will be demonstrated by intelligent readers." History has taught that Lodewijk Elzevir's concerns about a possible lack of interest in Galilei's book had no basis.

The *Discourses and mathematical demonstrations related to two new sciences* is the seminal work of the scientific method, and reading this book is enlightening not only for physics students and professors but also for all science enthusiasts, and for anyone who wants to understand the history of human thought. The consideration, at the basis of this dialogue, that experiment and demonstration are the key tools for understanding nature, represents an imperishable message even in its apparent simplicity. The wonder at Galilei's persuasive demonstrations and the simple examples and experiments he proposed to support his arguments broaden the mind and nourish the culture of curious readers.

We must be truly grateful to Alessandro De Angelis who made this Galilei's book, which is at the foundation of all modern science, pleasant to read even for today's readers, accustomed to the use and abuse of the scientific culture of Wikipedia, and who gives with this work of his is a very important contribution to the understanding and interpretation of Galilei.

CERN, Geneva, Switzerland

Ugo Amaldi
Physicist, researcher and teacher
President Emeritus of the TERA
Foundation for Oncological Adrotherapy

Preface by Telmo Pievani

According to Galileo Galilei, the book of nature is written in mathematical language: more precisely, its "characters are triangles, circles, and other geometric figures." Alessandro De Angelis, four centuries later, translates Galilei's book of nature in algebraic terms. Whether you observe it synthetically from above or analytically from below, the revolutionary matter of the *Dialogues* you are about to read does not change. However, here is the bet, paraphrasing it makes it more readable, and its argumentative structure becomes clearer. Of course, laying hands on late Galileo's masterpiece and translating it into modern language is a difficult task, but here it is faced with the utmost seriousness.

There is a precedent. The decipherer of the secrets of stellar evolution, the 1983 Nobel Prize in Physics Subrahmanyan Chandrasekhar, in the last years of his life, between 1990 and 1995, had ventured into a similar work with Newton's *Principia*. He had rewritten the *Philosophiae Naturalis Principia Mathematica*, also in that case replacing geometric reasoning with formal mathematical notation, selecting the crucial moments, and extending the demonstrative passages. Newton's expert scholars, while applauding the attempt in itself, had however noted a series of interpretative distortions due to insufficient consideration of the historical context. The underlying problem lies indeed in the actualization, in the residual infidelity of each translation, and in the risk of introducing anachronisms. De Angelis did not let himself be dissuaded by such a precedent and brought to completion a project he had in mind since his juvenile studies. So here he rewrites for modern readers the *Discourses and mathematical demonstrations related to two new sciences concerning mechanics and local movements* by Galileo, which precedes the Newtonian *Principia* by fifty years and, by explicit admission of Newton, deeply inspires them.

However, there are some differences with the work of Chandrasekhar, all in favor of the *esprit de finesse* of De Angelis. Here the version is unabridged, except for a few and delicate reductions and additions: it is not a miscellany, therefore the arbitrariness of the selection is avoided and the work is returned to the reader in its entirety, including the additional day of dialogue on the force of percussion. There is notable attention to the history of criticism, to the context of the time and to the literality of the text, also in the use of the original drawings probably attributed to the hand of Galilei himself, at least for those of the first three days, as well as in the choice of adopting only the mathematical tools known at the time in Europe. So it is in some respects a version of the *Discourses* as Galileo himself could have written it, had he not made different choices on the basis of his knowledge. Furthermore, the language is paraphrased in an informal and cordial tone, with a refined and accurate set of notes related to style, content, history, and bibliography. Finally, the merit of De Angelis is to make all his methodological choices transparent in the Afterword. The result is a truly rigorous divulgation, which has also the interesting effect of making the *Discourses* more similar to the *Dialogue concerning the two chief world systems* published by Galileo six years earlier.

Indeed, this book also faces another challenge. We know that Galileo's prose, a model of Leopardi's, made Italo Calvino say in 1967 that he was the "greatest writer of Italian literature of all times," a combination of precision, evidence, and lyricism. We also know that this was not just a question of style. To counteract the obscurity and verbiage of the academic and ecclesiastical authorities, Galileo put in place a real strategy of cultural policy. He wrote in vernacular Italian to reach all who were curious enough to open up to the new vision of the cosmos, and perhaps capable of being excited by the unfolding of an open Universe and of a map of the world largely to be explored yet. The ideas of a new astronomy and new physics thus also became a theatrical tale and public debate. Yet, as De Angelis points out, when Galileo writes he is not always clear and linear.

Although being also written in dialogical and narrative form, the *Discorsi* in their original version are presented as a strange hybrid of vulgar and Latin, almost a step behind the *Dialogue*. They contain convoluted sentences, rather difficult paragraphs, passages that are not always explicit. Perhaps the rush of the last years, or the fears of Galilei after his trial, make the book difficult to read. Also, although the characters are the same as in the *Dialogue*, the roles the three play on stage are less intuitive. There are no more the peripatetic, the Copernican, and the connecting figure between the two, but different phases of Galilei's own scientific thought are dramatized, from youth to maturity. With a genial choice, the *Discorsi* thus become an entirely interior theater, the story of an intellectual parabola, a succession of hypotheses, discoveries, experiments, and demonstrations that are transferred from the scientist's head to the voices of the various characters. A scientific revolution is seen as it unfolds, from the inside.

Indeed, already in the *Dialogue*, if reread today, Simplicio can appear, rather than as a caricature of the opponent (or a polemical reference to some Aristotelian colleague of the time), as a splendid rhetorical move to put yourself in the other's shoes: try to imagine yourself as a Ptolemaic physicist and see what absurd consequences you will come to. The rest, net of style, is Galileo's well-known gait, rendered vividly here: the concrete examples, the stories of real experiences, the clear arguments, the extreme cases that challenge common sense. Here, you will read of cats falling from great heights without getting hurt, of vibrating chords, of theoretical digressions on the one and on infinity, of how sturdy animal bones must be, and of course of inclined planes, pendulums, projectile ranges. There are the physics of space, time, and movement, the principle of inertia, the isochronism of pendulum's oscillations, the acceleration independent of their masses in the free fall of bodies, and a lot of intelligence and beauty. But above all, thanks to De Angelis' paraphrase and algebraic translation, the genesis of Galilean ideas is better understood: not only the consolidated results, almost as if they were timeless, but the process of discovery, the concrete intellectual labor that led to their formalization. While the three friends discuss amiably, there is a world that dies, that of the traditional Renaissance academies, and a world that is emerging, the one of experience, engineering technique, the useful work of "vile mechanics."

There is still another reason to appreciate the timeliness of this work. The discourses and demonstrations you will read here owe to the lecture notes and experimental notebooks dating back to Galilei's happy Paduan period, from 1592 to 1610. Probably most of the experiments mentioned here were conceived and conducted in Padua. The characters of the Galilean narrative fiction revolve in various ways around the University of Padua and its lively intellectual environment. The book is dedicated to the Count of Noailles, for his decisive intercession in having it published (a few years after the *Dialogue concerning the two chief world systems* had been banned) in Leiden by the typographer Lodewijk Elzevir; the count had been a pupil of Galilei during his teaching period in Padua. In short, between the lines of these cordial dialogues, the University that welcomed him and gave him great freedom of research, and which in 2022 will celebrate its first eight hundred years, is omnipresent. It is therefore particularly significant that this excellent work by a scientist and professor from the University of Padua sees the light in conjunction with this impressive anniversary. From Galileo's Padua to today's Padua.

Ludovico Geymonat wrote that in the *Discourses*, together with Galileo's typical persuasive and defensive narrative, the interpenetration of mathematics and experience that will be the basis of all modern science is brought to perfection. There are epochal books, root books, and the last work of the "first mathematician and philosopher of the Grand Duke of Tuscany" is one of those, here for the first time made fully accessible to the curious readers. So it happens that a learned scientist of today, a particle physicist and astrophysicist of the twenty-first century, aware of the importance of the history of scientific ideas, manages to give us back that imperishable feeling that Galileo himself, on the fourth day of these *Discourses*, describes by writing that "the force of demonstrations such as occur only in mathematics fills with wonder and delight."

Telmo Pievani
Chair of Logics and Philosophy of Science
University of Padua, Italy

Introduction

Modern readers face major obstacles in reading Galilei, because his geometric reasoning, which irradiates culture in deference to his great Greek masters, is completely different from today's notation-dominated mathematics. This fact makes his demonstrations difficult to follow. In addition, he uses a rich and complex language, with long periods, double negations, and multiple levels of indentation. As a consequence of all of this, Galilei is extremely difficult to read and understand. understand.[1] But none of this negates the fact that he is one of the fathers of science and modern culture, as well as being quite witty and funny, and that everybody would therefore be enriched by being exposed to such artistry, such intelligence and such beauty, or, to use a more Galilean expression, by experiencing such a marvel.

This work is a translation of the *Discorsi e dimostrazioni matematiche intorno a due nuove scienze (Discourses and mathematical demonstrations related to two new sciences*, in short, *Two New Sciences*), the fundamental book by Galilei dedicated to mechanics, into modern English (largely refreshing the 1914 translation by Crew and De Salvio), and in algebraic formulae. It is written with the purpose of making Galilei comprehensible to what I imagine "modern" readers to be when I think of my children: curious, passionate about science, but, unfortunately, with little time to dig into lexical, historical, and philosophical antiquities. An operation of this kind had been carried out by Subrahmanyan Chandrasekhar with Newton's *Philosophiae Naturalis Principia Mathematica (Mathematical Principles of Natural Philosophy,* often simply called *Principia*). In contrast to Chandrasekhar's approach, I restricted myself to the mathematics available in Galilei's time (and thus, in particular, I avoided calculus), and I tried, where possible, to trace Galilei's line of thought.

[1] Despite its difficulty, Galilei's language, according to many Italian writers, sets a fine template for literature. Italo Calvino writes that "[...in particular when writing about the Moon] Galilei, the greatest Italian literature writer of any century, raises his prose to a degree of accuracy and evidence combined with a prodigious lyrical rarefaction. And the language of Galilei was one of the models of Leopardi, great lunar poet."

I chose to use, with a few exceptions justified in the Afterword, the original images, extracted and digitally cleaned ex novo from their initial appearance, because of their artistic nature, and because many historians (including Antonio Favaro, the editor of the national edition of the Opera Omnia of Galilei, which we refer to simply as the "national edition" in the following) attribute them to Galilei himself, who was well known for his facility in the art of drawing.[2] Thanks to the use of modern image-cleaning technologies and to the extreme care of the staff at the Biblioteca Nazionale Centrale di Firenze, I feel certain that the reproduction of the figures in this work is more faithful to the originals than in any other edition after Galilei's time.

Two New Sciences, published in 1638, was the final book released by Galileo Galilei (1564–1642). It presents a scientific work performed over the course of Galilei's life. The events described begin in 1602 and involve a long phase of meditation and discussion with numerous correspondents, Paolo Sarpi in particular, on the concepts of space, time, and movement. Galilei began writing the first draft in 1608, but in 1609, new inspiration struck: he learned of the invention of the telescope and soon developed a passion for this new instrument, subsequently improving it and becoming totally absorbed in astronomical observations for a period of several years. The writing of *Two New Sciences* became central again after 1633, following the publication of the *Dialogo sopra i due massimi sistemi del mondo (Dialogue concerning the two chief world systems)*. In addition to many original subjects, *Two New Sciences* includes topics from the *De motu*, written around 1590 and never published, and lecture notes and experimental notes dating back to the Padua period (from 1592 to 1610: "the best eighteen years of my life," according to Galilei),[3] also never published before. It represents the summa of his physical thought, just as the Dialogue concerning the two chief world systems is the summa of his cosmological thought.

The two new sciences Galilei refers to are the science of materials (related mostly to the science of construction), addressed on the first two days of discussion, and mechanics, addressed on the third and fourth days. In this work, I have chosen to include the additional day of discussion related to the strength of percussion and the origin of motion, i.e., the way movement is transmitted to a body. Galilei initially wanted to include this chapter in the first edition, as he writes twice, in the text and in a letter to the editor. By the time of publication, however, Galilei had concluded that this material was not yet sufficiently developed, and thus its release was postponed; it would not see the light of day until after his death. Having chosen to include this material, I also chose not to include an appendix on the center of gravity of solids that Galilei had composed in his youth, and that had been

[2] My personal opinion, also justified by the stylistic comparison with the Galilean manuscripts kept in the Italian National Library in Florence and by the progression of Galilei's blindness, is that it is likely that the figures from the first three days are attributable to Galilei, while those from the fourth day and the additional day probably are not.

[3] Letter to Fortunio Liceti, Arcetri, June 1640.

unpublished (eclipsed—as Galilei says—by Luca Valerio's *De centro gravitatis solidorum*) until it was added to the first edition of *Two New Sciences*.

Two New Sciences is one of the most important works in the history of science: it paved the way for Newton's *Principia*, published half a century later, and to experimental science in general. Newton recognized not only Galilei's authorship of the first law of dynamics, the so-called principle of inertia, but also his contribution to the second, which establishes the proportionality between force and acceleration.[4] *Two New Sciences* contains, to mention only some of its main discoveries, the principle of inertia, the description of the motion of falling bodies, the observation that bodies of different weight fall with the same acceleration in vacuo, a demonstration (correct only at the first order) of the isochronism of pendulum oscillations, a demonstration of the parabolic motion of projectiles, and innovative considerations related to acoustics and music. For the first time, physics, the science of nature, as Aristotle called it, is expressed through mathematics. For the first time, experiments are designed and performed to test hypotheses. Galilei was clearly aware of the important legacy that he was leaving, and often writes about this fact in the text. Hawking places this book among the five fundamental works in the history of physics and astronomy, and according to the mathematician Alfréd Rényi, this is the most significant mathematical work in over 2000 years.

Two New Sciences is written in the same style as the *Dialogue concerning the two chief world systems*, with the same three characters (Simplicio, Sagredo, and Salviati) engaged in discussion. Two of them were inspired by real people, friends of Galilei's: the Florentine Filippo Salviati, a member of the Accademia dei Lincei, like Galilei, and the Venetian Gianfrancesco Sagredo, formerly a pupil of Galilei's. The third character is Simplicio, a fictional character whose name is the same as that of an ancient commentator (VI Century a.D.) of Aristotle. His name implies a

[4]The two laws are enunciated as follows in the Principia [52]:

> Lex I: Corpus omne perseverare in statu suo quiescendi vel movendi uniformiter in directum, nisi quatenus a viribus impressis cogitur statum illum mutare

(All bodies persist in their state of rest or of uniform rectilinear motion until forces applied to them make them to change this state), and

> Lex II: Mutationem motus proportionalem esse vi motrici impressae, et fieri secundum lineam rectam qua vis illa imprimitur

(The change in motion is proportional to the motive force impressed; and is made in the direction of the straight line in which that force is impressed). Newton writes then:

> Per leges duas primas et corollaria duo prima adinvenit Galilaeus descensum gravium esse in duplicata ratione temporis, et motum projectilium fieri in Parabola, conspirante experientia, nisi quatenus motus illi per aeris resistentiam aliquantulum retardantur

(By means of these two first laws and of their corollaries Galilei found that the distance descended by heavy bodies increases with the square of time and that the motion of projectiles takes place along parabolic trajectories, as experiments confirm, neglecting some delay due to the mobile strength).

certain scientific simplicity. Simplicio often plays the role of an Aristotelian professor (a “peripatetic,” as described in the text, from the name of Aristotle’s school), and, as such, is not particularly critical. Sometimes, Simplicio’s arguments represent the opinions of the young Galilei, Sagredo represents his middle age, and Salviati is the author in his mature age.[5] In their discussion, the three friends frequently comment upon a text written by an Academician who taught in Padua, clearly Galilei himself; they often refer to him simply as the Author, or the Academician, or sometimes even “our friend.” The Author’s text (quite formal, different from the dialogical part of the book) is in Latin in the original; I have transcribed it in Italics for clarity. On the additional day on the strength of percussion, which discusses the way in which movement is communicated by an impulsive force to a body, Simplicio is absent, and is replaced by Paolo Aproino from Treviso, who had been a student of Galilei’s in Padua and had assisted him in some of his experiments on motion, together with Daniele Antonini from Udine. In addition to being more compelling than a treatise, as Plato had already shown and as prescribed in numerous courses on rhetoric of the time, a dialogue allows for circumventing formalism in certain demonstrations that Galileo was probably not able to develop rigorously, often due to the insufficiency of mathematics before the invention of calculus. Unlike a mathematical treatise, which follows the rule that each proposition must have been proven before moving on to the next (and the part of the book written in Latin is, indeed, a mathematical treatise), a dialogue allows its participants to forego certain rigorous demonstrations and replace them with assumptions of sufficient plausibility. In this sense, we see a role for the ambiguous meaning of the Latin word *demonstratio*, which had already been used by Cicero to signify both the act of showing, indicating and exhibiting, and the proof or formal demonstration in the mathematical sense.[6] Galilei shows here his deep knowledge of Plato’s dialogues and of the tools and recipes prescribed in the classical rhetorical handbooks of Aristotle and Cicero, carefully weighing cogency, emotion and elegance as ingredients to achieve persuasion.

[5]In his *Dialogue*... Galilei introduces the characters as follows (from the translation by Drake): “Many years ago I was often to be found in the marvelous city of Venice, in discussions with Signore Giovanni Francesco Sagredo, a man of noble extraction and trenchant wit. From Florence came Signore Filippo Salviati, the least of whose glories were the eminence of his blood and the magnificence of his fortune. His was a sublime intellect which fed no more hungrily upon any pleasure than it did upon fine meditations. I often talked with these two of such matters in the presence of a certain Peripatetic philosopher whose greatest obstacle in apprehending the truth seemed to be the reputation he had acquired by his interpretations of Aristotle. Now, since bitter death has deprived Venice and Florence of those two great luminaries in the very meridian of their years, I have resolved to make their fame live on in these pages, so far as my poor abilities will permit, by introducing them as interlocutors in the present argument. Nor shall the good Peripatetic lack a place; because of his excessive affection toward the Commentaries of Simplicius, I have thought fit to leave him under the name of the author he so much revered, without mentioning his own. May it please those two great souls, ever venerable to my heart, to accept this public monument of my undying love. And may the memory of their eloquence assist me in delivering to posterity the promised reflections.”

[6]See the Latin-Italian Dictionary by Georges and Calonghi, Rosenberg & Sellier, Turin 1950.

Since his previous book, the Dialogue, had been banned by the Church, Galilei had some trouble finding a publisher. He finally succeeded with Lodewijk Elzevir, a publisher working in Leiden, South Holland. It is most likely that the intercession of the Count of Noailles, who had been a pupil of Galilei's in his teaching period in Padua, and to whom the book is dedicated, was decisive. Elzevir wrote a beautiful preface, full of culture.

About 500 copies of the book arrived in Rome and were quickly sold. A copy reached the French mathematician Mersenne, who wrote, in the following year, a book entitled The new ideas of Galileo. Another copy reached René Descartes, who read it quickly and immediately exchanged letters with Mersenne, criticizing some of the demonstrations from the fourth day. Galilei received his author's copies only six months later, and he complained about this delay.

The word "mathematics" in the title of the book needs clarification. Although this book speaks of nature in mathematical language, Galilei, like Newton, manipulated algebraic formulas in a limited way, using geometry instead[7]: "[The Universe] is written in mathematical language, and the characters are triangles, circles, and other geometric figures, without which it is impossible to understand the world; without this, we wander around in a dark labyrinth."[8] Formulae like $F = ma$ and $E = mc^2$ are central to today's physics, but the algebraic and analytical approach was introduced by Descartes and others in the same century in which Galilei and Newton were writing their fundamental works. Galilei, like Newton in the Principia, did not use algebra, the new language: he used geometry instead, celebrating the tradition of Greek culture above the modernity of the analytical approach. The result of the complex mathematical-geometrical and literary structure of the book is, quoting Plonitsky and Reed, that "the quantity and level of mathematical argument is sufficient to dissuade many nonmathematically inclined readers from penetrating very deeply into the text. On the other hand, the text is by no means purely mathematical in nature, and the nonmathematical aspects may, in a perverse manner, dissuade the mathematically inclined from taking the text as a whole seriously enough to give it more than a selective reading. This combination, although found elsewhere in Galileo's works, presents particular complexities here, and this may help to account for the relatively low level of readership of the *Two New Sciences* and the prevailing, somewhat stereotyped views of the book."

Some comments for the readers. To avoid overloading the text, I used two types of notes. Those identified by a literal apex are reported at the bottom of the page, and they will not only help readers, but hopefully also amuse or amaze them; these notes are also used to indicate mistakes (according to the current physical theories) made by Galilei. Those identified with Arabic numerals are shown at the end of the book, and are quotations or comments that can be skipped at first reading. I tried to minimize the use of mathematical symbols to keep this book at a high-school level, and among the unusual symbols that I do make use of are "$\propto$" (proportional to),

[7]Aristotle (*Metaphysics*, 1025b2; *On the heavens*, 299a15) was convinced instead that the possibility of applying an exact science such as mathematics to real phenomena is limited.

[8]G. Galilei, *Il Saggiatore*.

"$\equiv$", (equal by definition to), and of the logical symbol "$\Rightarrow$" (implies that). I indicate with $|AB|$ the length of the segment AB. Finally, to make it easier for professional readers to relate the present translation with the original work by Galilei, references are provided at the margins of the text to the pagination of Vol. VIII of the national edition.

To make Galilei easy to read, I have benefited from the collaboration of many friends and colleagues, and I made some compromises; to keep this introduction light, I will discuss all of this in the Afterword, which also describes and justifies my stylistic choices and those related to the selection of the original material, as well as containing a brief bibliography of previous interpretations of this book. To those readers who, hopefully stimulated by reading this book of mine, will want to access the thought of the Author directly in his own language, I recommend reading the wonderful national edition by Favaro, suffused by a culture that I fear no longer exists in the present day, but by which, fortunately, we can be enlightened thanks to the eternity of the printed word. This book is dedicated to Antonio Favaro.

Alessandro De Angelis
Chair of Experimental Physics
University of Padua, Italy

Galilei's Units

During Galilei's life the second was an astronomical standard, but it was not a practical unit for terrestrial events. The grain of weight of the pharmacist was practically a standard throughout Europe, but it was too small for ordinary measurements. The pound, a weight unit, had different values in different countries. Length units such as the foot and the arm, in Latin called cubitus (we will call it cubit),[9] varied even more: in Italy the cubit, or braccio, indicated different lengths from one city to another, and within different centuries in the same city. Galilei did not use decimal fractions, but calculated only ratios of integers, which made small units advantageous.

Here, we report the units mostly used by Galilei for his measurements, and their translation in units commonly used today.

Space

Mile	1.65 km
Spear (lancia, picca)	3.6 m
Canna	4 cubits $\simeq$ 2.3 m
Cubit	57 cm
Foot	Half a cubit $\simeq$ 28 cm
Palm	1/3 cubit $\simeq$ 19 cm
Inch	2.5 cm
Finger	Qualitative
Punto	$\lambda \simeq 0.94$ mm

[9]The cubitus, already used by the Egyptians (an Egyptian cubitus corresponded to about 45 cm), is one of the oldest units of measurement of length; it is the distance between the elbow and the tip of the middle finger.

Note that the "punto" (point) is about the smallest distance that the naked eye can appreciate.

Weight

Pound	340 g
Ounce	28 g
Drachm	3 g
Denaro	1.2 g
Grain	52 mg

Time

In most of Galilei's demonstrations, an absolute measure of time was not needed; equalization of times, which could be performed using the acoustic phenomenon of beats, was enough. Using beats one can compare times with an accuracy of about 1/25 of a second. Galilei's ear, thanks also to the education given by his father, was particularly sensitive—he writes on the first day that in the fifth consonance he can feel the difference between the instants when only one of the two components is at maximum and the one when both are.

Galilei uses in the *Two New Sciences* a unit of time not very precise, the pulse-beat, and the count of oscillations of pendulums (and their beats). In his notes, he uses instead a more precise quantitative measure: the "tempo" (time), defined using a water clock more accurate than described on the third day of the *Two New Sciences*. The "tempo" corresponds roughly to the flow time of 1/30 ounce (that is, 16 grains) of water through his water clock, and it was about the smallest range appreciable with this technique.

Tempo $\tau \simeq$ 1/92 of second.

With these units, by measuring time in *tempi* and distance in *punti*, one has for the gravitational acceleration at the Earth's surface

$$g \simeq \frac{\pi^2}{8},$$

which rationalizes the relationship between length L and square of the period T ($T^2 = 4\pi^2 L/g$) in pendulums. The "tempo"'s fine calibration was likely performed in this way.