Chapter 3
Galileo's Private Course on Fortifications

Galileo taught privately in Padova from 1592 to 1609. He offered lessons on a variety of subjects, which, taken together, amounted to a complete course on fortifications typical for the end of the sixteenth century. Individual topics covered by Galileo's course on fortifications included: the use of mathematical instruments; practical arithmetic and geometry; military architecture; the practical science of machines, with an emphasis on those machines needed to build and maintain fortresses; as well as elements of theoretical geometry, drawing techniques including perspective, geodesy and elements of astronomy, typically in the context of what was held to be the subject of lessons on *La sfera*, namely practical astronomy.

The balance sheet of Galileo's workshop, that is, manuscripts 26 and 29, part of which were published by Favaro as the *Ricordi autografi*, represents the main documentary evidence of Galileo's activity as a private teacher.[1] Private lessons complemented his activity as an instrument maker. The military compass, in particular, was the didactic tool which students used to complete their exercises, and lessons on the use of the compass served as the core of Galileo's overarching course on fortifications.

As a rule, the entries in the *Ricordi* concerning private lessons are labeled according to their topic. These topics are: Geodesy, Mechanics, *La sfera* and Cosmography, Perspective, Euclidean Geometry, Arithmetic, Fortifications (that is, military architecture), and Use of the Military Compass. The fact that all registered topics, taken together, correspond to a rather typical treatise on fortifications of its day, is confirmed through comparison of his courses' contents with, for example, a traditional well-known contemporary treatise on fortifications: *Le fortificationi* (Lorini 1609) by Boniauto Lorini (ca. 1540–ca. 1611).[2]

---

[1] The text of the *Ricordi autografi* was introduced in the previous chapter, for it is also the main historical evidence of Galileo's activity running a workshop. For more details, see pp. 24ff.

[2] Bonaiuto Lorini's treatise was published in Italian for the first time in 1597. In 1609 he published the second edition, which is the one considered here.

M. Valleriani, *Galileo Engineer*, Boston Studies in the Philosophy of Science 269,
DOI 10.1007/978-90-481-8645-7_3, © Springer Science+Business Media B.V. 2010

In the sixteenth century, it was customary for young noblemen to study and earn a university degree. After these studies, the next standard career step was service as a military officer. In preparation for this, their university curriculum generally included a "course on fortifications." The university offered a basic level of instruction, while the highest level was available through private lessons, usually given by the university lecturer and/or in private academies. The course on fortifications comprised several topics, the aim of which was to make the future officer familiar with the knowledge needed on the battlefield. These subjects were military architecture; the use of relevant mathematical instruments; practical arithmetic and geometry; drawing techniques; the use of artillery; and the use and understanding of machines like water lifting machines, machines for pounding gunpowder, and any other weight lifting machines that could be useful in such places as fortresses, battlefields, harbors, and ships. The courses generally also provided some general notions of practical astronomy: for example, what was needed to "read" the sky, and to calculate positions and times. Courses on fortifications differed from each other in terms of the details they offered on the individual topics, or in terms of the instruments the students were taught to use.

Galileo's course on fortification was distinguished primarily by the fact that it was an all-inclusive service. Galileo's pupils lodged in his house with their servants; from the workshop of their teacher, residing in the very same house, they received the mathematical instruments that functioned as the hub around which all of the lessons revolved. Furthermore, their teacher was able to provide them with treatises he had written on most of the subjects. Finally, in most cases their teacher was also their professor at the university. In fact, most of Galileo's public lectures at the University of Padova served as introductions to the topics of his private lessons. The rolls of the university (*EN*, XIX:117–119) testify that the topics Galileo taught for eight of the eighteen years he worked at the University of Padova were Fortifications, Mechanics, *La sfera*, the Theory of the Planets based on Ptolemy's *Almagest*, Euclid's *Elements*, and Aristotle's *Mechanical Questions*.

In the following, first the structure and the magnitude of Galileo's business of private instruction will be described. The contents of his lessons then will be analyzed by means of a comparison with the state of the art of each individual subject. These contents are, first, training in the fields of practical mathematics and geometry, that is, subjects like drawing techniques, perspective, stereometry, surveying, and the use of relevant mathematical instruments; second, military architecture; third, the use and function of artillery; fourth, practical astronomy; and fifth, the science of machines.

The Structure of the Business

A cursory glance at the *Ricordi autografi* reveals that Galileo's house was anything but the studio of a lone thinker, as it was inhabited by dozens of residents at any given time.

Private students who were also lodgers[a]	Other private students
Schweinitz G. (+2)	Allfeldt (von) C.
Lazocski (+1)	Filippo d'Assia
Lentowicz M.	Vinciguerra Coll'Alto
Bucau B. (+1)	Reisener B.
Buc	Luzimburg
Plesch M.	Noailles (de) F.
? Giovanni - from Lithuania	Batavilla
Ferrante (+1)	Reigesberg G
Ricques D.	Dietrichstein (de) P.
Zator G. (+8)	+3 Students whose names are unknown
Lesniowolski R.	
Soell G. C.	
Het B.	
Montalban A. (+2)	
Morelli Andrea (+1)	
Caietano Giulio Cesare (+1)	
Total: 33 persons	Total students: 28

[a] The number in parentheses is the number of servants and/or companions accompanying the student.

Galileo's private students Galileo's private students were often the offspring of distinguished, or at least rich, families who wanted to complete the curriculum at the University of Padova before starting their military career as officers or as diplomats (Valleriani 2001). For example, during the period between 1602 and 1604 alone, as demarcated by the letter to Guidobaldo del Monte[3] about the isochronism of the pendulum, and the one to Paolo Sarpi[4] which gives indications of Galileo's construction of the theory of motion, as many as twenty-eight private students are listed in the *Ricordi* (see table above), sixteen of whom also lodged at his house for either the entire period or part of it. Moreover, most of his lodgers were accompanied by at least one servant or companion, so that the total number of roomers documented during that period actually increases to thirty-three.[5]

Treatises for the lessons Four of the subjects of instruction were based on Galileo's treatises entitled *Delle macchine* (Galilei 1592–1593a), *La sfera ovvero Cosmografia* (*EN*, II:203–255), *Trattato di fortificazione* (*EN*, II:77–146), and *Le operazioni del compasso geometrico et militare* (*EN*, II:335–424). Although Galileo

---

[3] Galileo to G. del Monte, November 29, 1602, in *EN*, X:97.

[4] Galileo to P. Sarpi, October 16, 1604, in *EN*, X:115.

[5] The names of Galileo's private students, as they appear in the table, have not been changed according to modern convention. The way they appear is the way Galileo wrote them in the *Ricordi autografi*.

published his treatise on the military compass in 1606, a first draft of his treatise on the use of the military compass had been prepared in 1599,[6] when the production of the instrument in his workshop became systematic. After all, there is copious evidence, both in his correspondence and in the *Ricordi,* that he was selling it to his students, besides proffering it as a gift to renowned personalities. The other three treatises were prepared by Galileo during the first years of his stay in Padova.

Further entries in the *Ricordi* testify that a copyist named Messer Silvestro was working at Galileo's house in 1603. The copyist provided the private students with handwritten copies of their teacher's treatises, including the one on the use of the compass.[7] Although the only entries regarding handwritten copies of treatises concern Messer Silvestro in 1603, this seems to have been a normal procedure in Galileo's house, as indicated by the several copies written by Galileo's pupils of his *Trattato della sfera*, *Delle macchine* that are still preserved today.[8]

The organization of the entire course The sequence of subjects taught by Galileo shows some regularities (Fig. 3.1). Almost all of the students were taking lessons on the *Uso del compasso militare*, alternating these lessons on the military compass with those specifically devoted to military architecture based on the treatise *Le fortificazioni*. All of the other subjects were taught by Galileo before these lessons. Galileo's teaching of mechanics based on the treatise *Delle macchine* was in particular demand. Galileo's reading of Euclidean geometry and perspective was also propaedeutic to the lessons on military architecture and on the use of the compass. They were oriented toward the practical needs of a military man faced with challenges such as designing fortresses, aiming a cannon, and surveying terrain. Most of the students who took the class on practical astronomy did so after completing those on mechanics, and before starting instruction on military fortification and the use of the compass. Finally, there is one entry in the *Ricordi* regarding lessons in geodesy, and one for arithmetic.

---

[6] Cosimo Pinelli to Galileo, April 3, 1599, in *EN*, X:73. More than one draft of the treatise on the use of the military compass exists that was compiled before 1606, when Galileo published it. Some of these previous writings have been published by Antonio Favaro. See *EN*, II:345–361.

[7] Galileo annotated the following set of entries concerned with Messer Silvestro's work in 1603: "Note of the copies from Messer Silvestro: Fortifications, 2 copies, for Lord Giovanni Svainitz and Lord Lerbac; The same, 1 copy to Lord Bucau; The same, 1 copy to Lord Alfelt; The same, 1 copy, to Lord Staislao; The same, 1 copy, to Lord Niccolò Beatavil. For one copy of the Use of the Compass, given to Lord Staislao. For one of the Use of the Compass, given to Lord Beatavilla. For one copy of the mentioned Use, given to the Most Illustrious and Excellent Lord Langravio. For one of the mentioned copies, given to a German nobleman. For one given to Lord di Noagles" (*EN*, XIX:163).

[8] Favaro's analysis of four handwritten copies of Galileo's *Trattato della sfera* shows that Galileo's students were also permitted to copy the treatises of their teacher themselves. This is the case, for instance, for Abbot Giugni's copy of that treatise, and Galileo himself wrote that Abbot Giugni was in his house (*EN*, XIX:163).

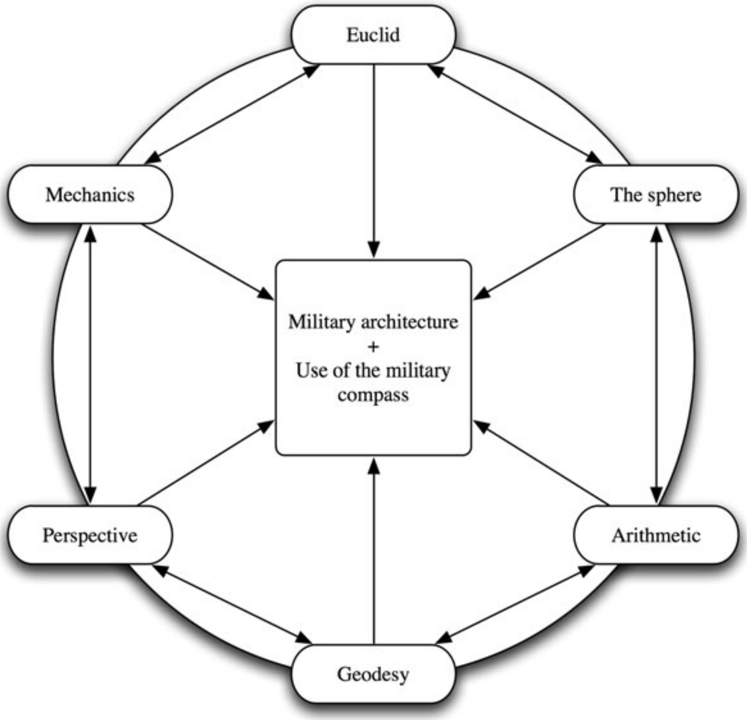

Fig. 3.1 The structure of Galileo's survey course on fortifications. The disciplines along the circumference were considered to be propaedeutic topics for those placed in the middle of the circle

Mathematics for the Military Art

The background of many of the subjects taught by Galileo consisted of notions on mathematics, practical arithmetic and practical geometry, that is, those disciplines that were often simply called mathematics.

In 1607 Galileo's friend Pietro Duodo was elected *Capitano di Padova* of the Venetian Republic, and he immediately founded an academy where the young noblemen of Padova not only were drilled in gymnastic exercises to practice for the cavalry and fencing, the usual activities offered by almost all the academies for young noblemen at the time, but, in accordance with the cultural and political context emerging in the early modern Italian cities, could also attend to learning the topics concerning the military arts.[9] This was the birth of the *Accademia Delia* of Padova, which issued a call for a lecturer of mathematics in 1610, for which position

---

[9] For the cultural change in favor of an education which included notions of military art, see the next chapter, pp. 117ff.

Galileo listed the required subjects of instruction during the same year. In Galileo's words:

> [1] It is primarily necessary to comprehend lower-level arithmetic, for the needs of regulating the armies and for many other eventualities.
> [2] Practice with geometry and stereometry, for measuring all planes on a surface, both regular and irregular, and for measuring all of the solid figures and bodies.
> [3] Knowledge of the mechanical sciences, not only about their reasons and common basis, but also regarding many machines and particular instruments, together with the resolutions of a great deal of questions and problems depending on that mechanical knowledge.
> [4] Practice with kinds of artillery, entailing knowledge about their differences, measures and proportions, as well as about the causes and reasons of many accidents which happen in this exercise.
> [5] Knowledge of the compass and of other instruments, for drawing all kinds of plans, both close and far away.
> [6] Use of instruments for measuring heights, distances and depths with the sight, and for leveling each site.
> [7] Some exact rules for drawing in perspective all of the things seen and imagined, by means of which the fortresses and all their parts, as well as each machine and war instrument, can be represented and visualized.
> [8] Military architecture, that is, perfect knowledge of the art of fortifying each site and area.
> [9] Instruction about the defense and attacks of fortresses.[10] (*EN*, II:607–608)

Functions of the military art Five of the points suggested by Galileo for the *Accademia Delia* course on mathematics correspond directly to what he was teaching in his lessons about the use of the military compass. The first point about the regulation of armies entails the teaching of those geometrical transformations that enable groups of soldiers to be positioned in specific, defined geometrical shapes on the battlefield, so that the army could change formation while marching, for example, starting from a semicircular formation to assume the shape of an advancing triangle of soldiers.[11] The second point describes the surveying functions an officer had to master. As mentioned in the previous chapter, measuring the dimensions of the main architectural elements of a fortress was extremely important during an attack, to ensure the proper positioning and loading of artillery.[12] On the basis of these measurements, officers were supposed to be able to draw a plan and a profile of the fortress. For all of these purposes, in points five and six Galileo also explicitly suggested teaching the use of mathematical instruments, presumably including his military compass.

Perspective as a drawing technique Drawing and surveying the plan and profile of a fortress required some experience with drawing techniques, ideally including drawing in perspective. This is not only proposed by Galileo in point seven of his notes for a course of mathematics at the *Accademia*

---

[10] Author's enumeration.

[11] The need to change the shapes of groups of soldiers on the field, and how Galileo's compass met this need, are described in the previous chapter on pp. 32ff.

[12] For fortress surveying and the related use of the military compass, see the previous chapter pp. 30ff.

Delia, but actually also was privately taught by Galileo himself as an independent discipline in the framework of the lessons concerning military architecture. Several entries in the *Ricordi autografi* indicate that Galileo gave specific private lessons on this topic. For example, on November 7, 1601 Galileo noted:

> On the seventh of November The Lord Counselor of the German Nation started Perspective (*EN*, XIX:150)[13]

where the Lord Counselor was a Mr. P. Dietrichstein.

Military Architecture

Practical mathematics and geometry found their most relevant use not merely as an intellectual background to the functions accomplished by mathematical instruments like Galileo's military compass. The new art of military architecture, which became established during the sixteenth century, was another discipline which necessarily presupposed such knowledge. Galileo wrote two treatises on military architecture; both approach the same topics, although one of them does so more extensively. They date back to the first years Galileo spent in Padova, as a handwritten copy of one of the treatises bears a date with the year 1593. One of the two treatises, the shorter, is entitled *Breve istruzione all'architettura militare* (*EN*, II:17–75), while the title of the longer is *Trattato di fortificazione*, as already mentioned. Antonio Favaro was probably right when he stated that the longer treatise was intended for private lessons, and the shorter for the public lectures held at the university (*EN*, II:9–14). Mostly, the longer treatise will be considered in this work.

Bonaiuto Lorini (1547–1611) To evaluate these of Galileo's treatises, they are compared with Lorini's treatise. According to Carlo Promis (Promis 1874, 638), Lorini was elected military engineer of the Venetian Republic in 1580. With some interruptions, he worked for the Venetian Senate for the remainder of his life. He was born in Florence, where he trained under the direct patronage of Cosimo I de' Medici, who also placed him under Buontalenti's tutelage. Lorini's treatise, which has been translated into many languages, was well known during his lifetime and for many years after his death.

Drawing techniques The treatises by both Galileo and Lorini begin with some elements of geometry, imparted in the form of definitions and basic drawing techniques, such as how to draw a line parallel to a given one. Whereas Lorini started with many definitions, Galileo opened by describing the actual techniques. In particular, he explained how to draw a line perpendicular to a given one, how to draw parallel lines, how to divide angles into equal parts, and how to draw some simple

---

[13] In Vincenzo Viviani's *Racconto istorico* the author affirmed that Galileo also wrote a treatise on perspective, as a text for his private lessons (*EN*, XIX:606). Unfortunately no copy of such a treatise has been ever identified.

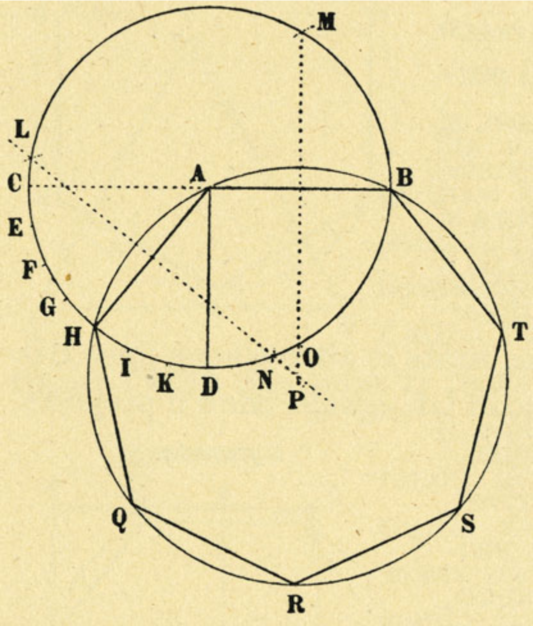

Fig. 3.2 Drawing technique to realize any kind of polygonal figure (*EN*, II:82)

polygonal figures. In fact, the main purpose of both authors was to teach how to draw any kind of polygonal figure whatsoever on the basis of only one rule (Fig. 3.2). Clearly, the objective was to enable students to draw plans of fortresses, which were generally designed in the form of some polygonal figure (*EN*, II:82; Lorini 1609, 16). Together with the propositions upon which the principle of proportion is based,[14] the Euclidean geometry involved in these drawing techniques was probably at least part of the contents of those lessons recorded under the name *Euclide* by Galileo in his *Ricordi autografi* (*EN*, XIX:155).

Attack and defense strategies After this introduction to basic geometry and the basic techniques of drawing polygonal figures, Galileo began the actual course on military architecture by explaining why fortresses are built. A fortress is built in order to allow a small number of soldiers to defend themselves against a greater number of enemies (like a force-saving machine!). Galileo elucidated the different attack and defense strategies usually used against or from a fortress.[15] In particular, he specified the five most common ways to attack a fortress: (1) opening the protective wall by means of artillery and then assault; (2) *zappa*, which means moving in close to the fortress wall and destroying it slowly with tools like picks and iron poles before assaulting; (3) scaling,

---

[14] The Euclidean principle of proportion is analyzed in the previous chapter on pp. 28ff.

[15] The issue of attack and defense strategies corresponds to point nine of the outline Galileo prepared for the mathematics curriculum at the *Accademia Delia*.

which means first moving in close to the fortress wall, then scaling it using ladders, and, finally, assault; (4) *mina,* which means mining underneath the fortress wall and then exploiting the advantage of surprise to assault; and (5) siege, which means simply waiting until the food and supplies in the fortress are depleted.

New defense and new design The sixteenth century experienced the diffusion of mobile heavy artillery powered by gunpowder, which immediately brought with it a new way of attacking fortresses. This subject was still considered particularly important at the end of the century, as the increasing frequency of wars made it increasingly necessary to fortify territories, villages and cities. In response to this situation a new conception of fortress was developed.[16] Galileo taught his pupils the main characteristics of such a modern fortress.

No point of the protective wall could remain concealed to the view of the soldiers inside the fortress, and therefore as few corners of the wall as possible were to be angled toward the interior. This is the reason why most of the new fortresses built in or after the second half of the sixteenth century have an external perimeter that follows a regular polygonal figure. However, it was not always possible to satisfy all of the complex contextual conditions required for the construction of a new fortress (Fig. 3.3). Thus in most cases the main task of the military architects was to renovate Medieval fortresses in order to adapt them to new military demands.

The bastion The bastion is a particularly relevant architectural element conceived to defend the fortress from cannons. This is a kind of superstructure built over the corners of the fortress and projecting toward the exterior. As this element became an established element in fortress design, a debate erupted among military

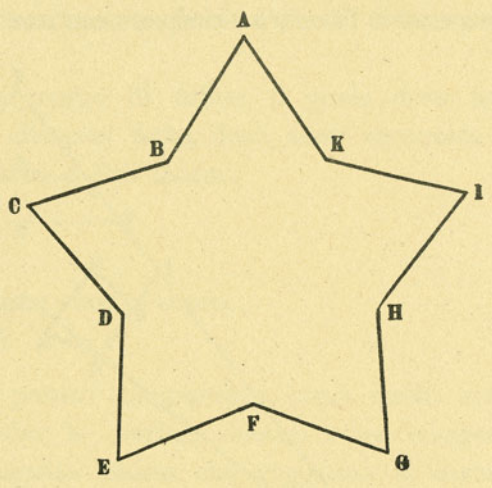

Fig. 3.3 Example of a fortress' plan (*EN*, II:85)

---

[16] For the development of the new early modern concept of fortress, see also Valleriani (Forthcoming b).

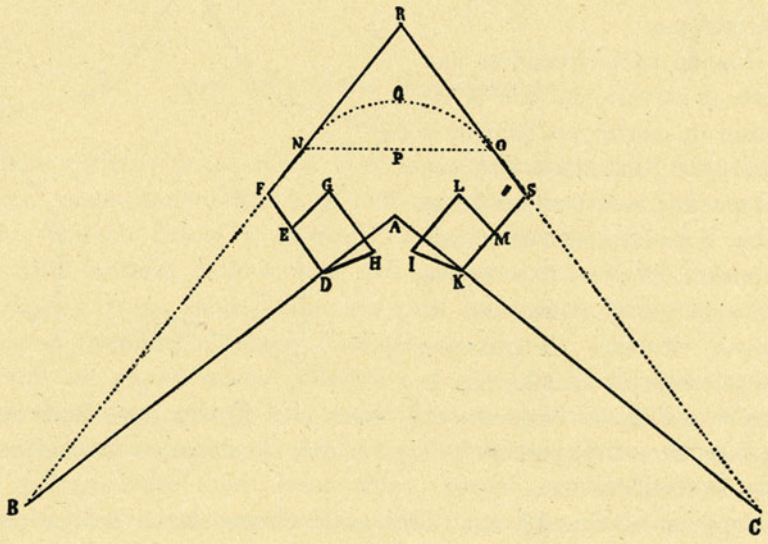

Fig. 3.4 Plant of a fortress' bastion (*EN*, II:86)

engineers about the shape for the stablest and most effective bastions. In truth, a bastion is a compound of many architectural elements (Fig. 3.4): A bastion (FDAKSR) is normally constituted of two strongholds (EDHG and IKML), where the heavy artillery was positioned; two associated shoulders, which are massive, protective walls for the strongholds (FEGN and LMSO); and the main stronghold (NOR). The two strongholds on the sides are located at a lower height than the main stronghold. A low stronghold together with its shoulder constitutes one flank of the bastion. Once the two lower strongholds had been equipped with artillery, their function was to defend the curtain (up to points B and C, for instance) in the eventuality that the enemy approached close to the curtain to scale it or attempt to destroy it manually. The function of the shoulders was to protect the two low strongholds from the enemy artillery positioned outside the fortress. From the main stronghold, which was protected by a parapet or rampart, the defenders of the fortress could use heavy artillery to launch attacks toward the fields across the moat.

The artillery positioned in the lower strongholds was the most effective defense against attackers, as the first goal of every attack was to penetrate some point of the fortress wall in order to be able to invade it, whereby the number of defenders was always smaller than that of the attackers. But in order to make a hole in the defensive wall that was sufficiently large to allow the attackers to enter the fortress, a series of other operations was required, including bridging the moat and preparing the ladders. Moreover, these time-consuming operations had to take place close to the wall. Therefore, while the attackers prepared an assault close to the wall, the artillery located in the lower strongholds executed what was called *passate*, very destructive cannonades along a line skirting and almost parallel to the wall of the fortress. This meant that an attack could not be launched until the artillery in the

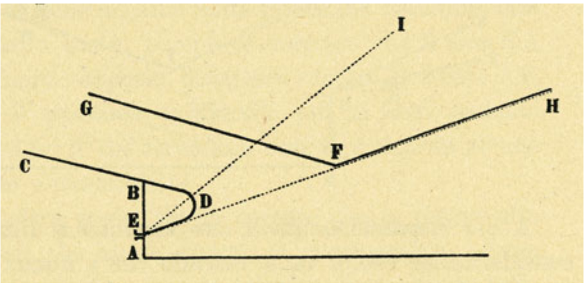

Fig. 3.5 Description of the function of the strongholds (*EN*, II:97)

strongholds had been put out of order. This is the reason why the primary target of any attacking army was always the artillery positioned in the lower strongholds.

Once the importance of the lower strongholds had been recognized, it became standard practice, as Galileo himself admitted and approved, to build additional bodies on the flanks of the bastion alongside the openings of the strongholds (Fig. 3.5). These were semicircular in shape and projected toward the exterior (BDE). They were called *orecchioni*—big ears—and their express function was either to preclude any practical possibility of shooting directly into the strongholds or, if this was impossible for architectural reasons, to force attacking artillery to shift its position further away from the strongholds but close to another point of the curtain, necessitating a dangerous maneuver like one from point I to point H.

The bastion's vulnerability Given the bastion's importance, or more precisely, its robustness, upon which the success of an attack or of a defence was directly dependent, military engineers addressed long and detailed speculations to their potential vulnerabilities. Galileo confronted this issue as well, detecting one main vulnerability that was "considered to be the main [problem] by most of the architects" (*EN*, II:94). This imperfection was related to the angle of the bastion, and therefore to the internal angle of the corner projected toward outside. According to Galileo, it was imperative that this corner not be too acute (Fig. 3.6) and this

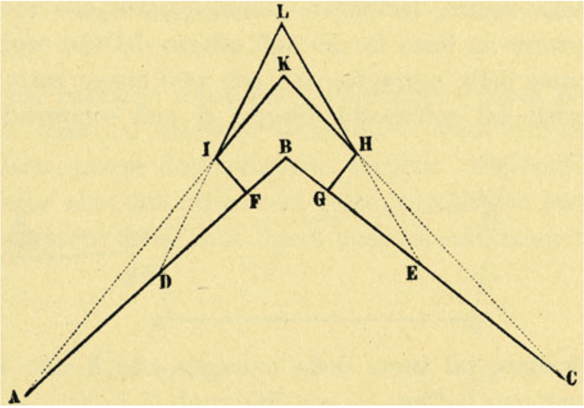

Fig. 3.6 Plan of a fortress' bastion with a corner built on an angle that is too acute (*EN*, II:95)

for two main reasons: first, because the corner would have been weak and easy for enemy artillery to cut off, and second, because the bastion would not have been wide enough for strongholds able to accommodate heavy artillery. Galileo identified three reasons for this imperfection. First, the corner is too acute when its angle inside the fortress is not obtuse; second, when the bastions are designed such that they could defend the curtain only as far as points very close to the same bastions like D and E (Fig. 3.5); third, when the flanks of the bastions were too long. As Galileo himself stated, these conclusions, especially the first and the third, were simple consequences of applying proposition 21 of the first book of Euclid's *Elements* (*EN*, II:95).

Galileo was only one of the many military architects who approached this important topic. The theme of bastion construction is discussed in almost any of this period's manuscripts or treatises on military architecture. Carlo Theti, for instance, addressed the same issue, but offered very different solutions. Since his focus was on how to change and improve fortresses built back in the Middle Ages, and therefore equipped with bastions that were either too small or had exceedingly acute angles, he did not propose any changes in the method of bastion construction, but suggested cutting them in such a way that their front would become more resistant (Fig. 3.7) (Theti 1588).

Lorini, too, devoted an entire chapter to the issue, but discussed it from the perspective of the sizes of the bastion's flanks and with reference to the kind of artillery to be deployed (Lorini 1609, 44–49). Gabriello Busca (ca. 1540–ca. 1605), finally, in his treatise of 1601, went back to Albrecht Dürer's studies on architecture and came up with the radical proposal of avoiding angular bastions altogether by making them round (Fig. 3.8) (Busca 1601, 126).

Elements of the fortress and cavaliers Galileo demonstrated his familiarity not only with the bastion, but with all of the other common architectural elements of a

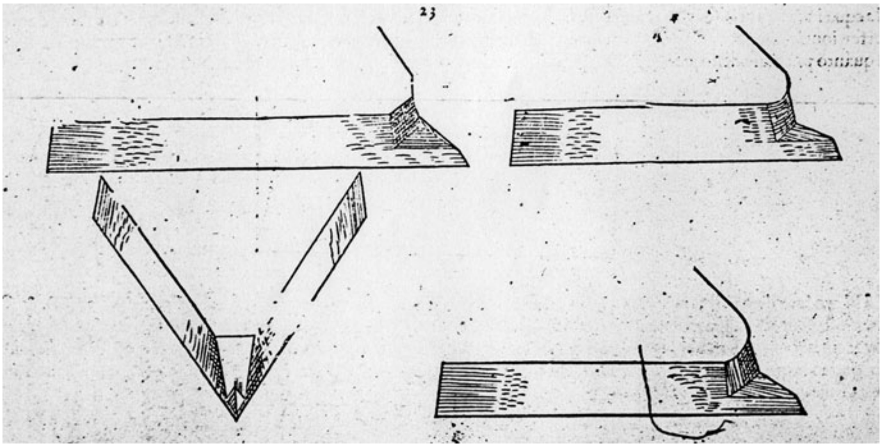

Fig. 3.7 Fortress bastions with cutted front (Theti 1588, 54)

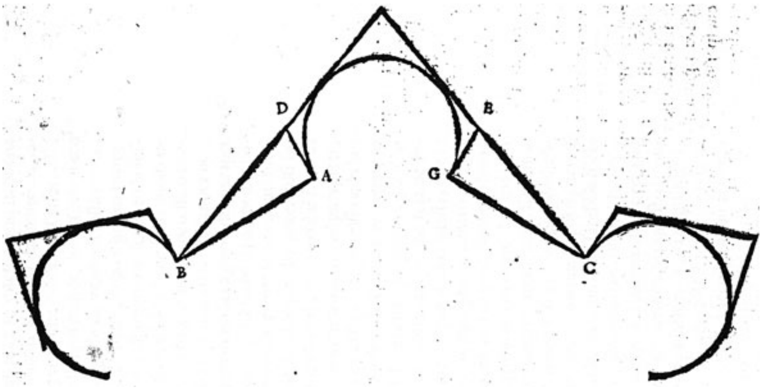

Fig. 3.8 Rounded fortress' bastions (Busca 1601, 126)

fortress as well. He diligently described the various kinds of cavaliers, strongholds, and platforms within the fortress as well as scarps, counterscarps, and covered walkways on its exterior. Moreover, he described how to build those structures outside the fortress which were needed in an attack. As mentioned in the previous chapter, the most important element that had to be built on the field to attack the fortress was the cavalier, a sort of tower as high as the lower strongholds, on which artillery was placed to shoot the cannons in the strongholds. Galileo described a method of building them using earth, reeds, and wood. In fact, this procedure, *del fortificar di terra*, was not only required by attackers launching a siege, but also turned out to be the fastest and most economical method of reinforcing old Medieval fortresses so that they could withstand the fire of the powerful new artillery developed during the sixteenth century.[17]

Quarto buono Officers had to know how to measure the inclination of the scarp (FH) and counterscarp (DEKFH) of the fortress (Fig. 3.9). This information was useful for several reasons. The inclination of the scarp was relevant primarily

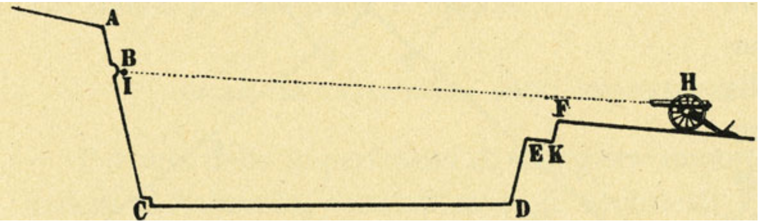

Fig. 3.9 Positioning artillery close to the scarp and the counterscarp (*EN*, II:96)

---

[17] The *Del fortificar di terra* procedure was used primarily during the sixteenth century in the Tuscan duchy (Lamberini 1990; 2007).

because this value could be used to determine the best intervals for positioning cannons, so that they could shoot perpendicular to the wall of the fortress at targets located as low as possible, preferably under the cordon. A second reason why it was important to know the inclination of the scarp was the practice of firing at the scarp itself to create small openings, into which the attackers closing in on the wall could lay harquebusiers to fire at the artillerists in the strongholds. This was possible only when the scarp was inclined at a relatively steep angle. Knowing the value of the inclination of the counterscarp was also useful in planning an assault at the wall, assisting the officers in determing the best method the soldiers could use to cross the moat.

For the purpose of measuring the inclination of the scarp and of the counterscarp, in the contexts of attacking a fortress, or to build them using earth, reeds and wood, Galileo presented an instrument conceived with the sole purpose of accomplishing this task. It was called *quarto buono*: the good fourth (Fig. 3.10). This instrument was not Galileo's invention.[18] Tracing the history of this instrument reveals a direct relationship between Galileo's treatises on military architecture and a particular circle of engineers and military architects. As Daniela Lamberini first pointed out (Lamberini 1990, 136–138; 2007), a tradition of treatises on fortifications became well established in the sixteenth century, starting with the manuscript

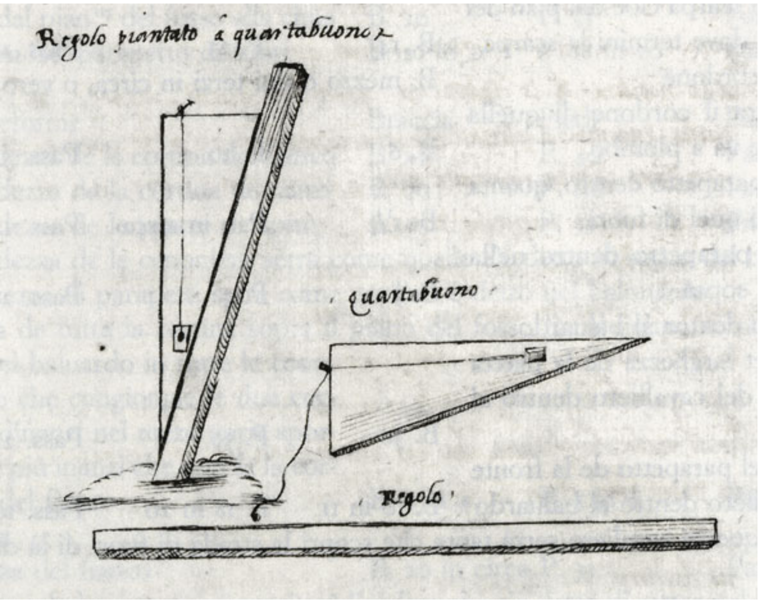

Fig. 3.10 Giovan Battista Belluzzi's illustration of the instrument called *quarto buono* (Belluzzi ca 1545, c. 27v)

---

[18] Galileo's compass can be configured to work as a *quarto buono* as well.

by Giovan Battista Belluzzi (1506–1554), a famous military engineer of the Grand Duke of Tuscany Cosimo I, entitled *Il Trattato delle fortificationi di terra* (Belluzzi ca. 1545).[19] Many copies of this manuscript circulated among the experts in military architecture during the entire century. In this situation the military engineers appropriated some of the contents of Belluzzi's manuscript and presented them as their own, in the form of either new manuscripts or of published treatises, according to the practice of the sixteenth century.[20]

In this context of exchange, entire paragraphs, sentences, and drawings originally by Belluzzi are found reproduced unchanged in many other sixteenth-century manuscripts and treatises on fortifications. Not only Bernardo Puccini (1521–1575), who was Belluzzi's pupil and thus officially in charge of expanding and editing Belluzzi's work, but also famous military architects like Bartolomeo Ammannati (1511–1592) and Bonaiuto Lorini were indebted to Belluzzi and Puccini. Many anonymous manuscripts still preserved at the *Biblioteca Nazionale Centrale* of Florence turn out to be more or less accurate copies of Belluzzi's and Puccini's treatises.

Galileo and Florentine military architecture There are three marks which distinguish those manuscripts on military architecture that emerged from the Florentine circle of military engineers: First, the emphasis on the fortifications made of earth, a method that achieved its widest diffusion upon the orders of Cosimo I; second, details like the description and drawing of the tools used by the sappers; third, the instructions and drawings for building the *quarto buono*.[21] Galileo's treatises on fortifications, which date back to the first years of his stay in Padova, include not only general statements similar to those in Belluzzi's manuscript, but also some of the same details, like the instructions for building the instrument *quarto buono*, clear evidence that his manuscript belongs to the Florentine tradition. In keeping with this theme, Horst Bredekamp and Daniela Lamberini accomplished a detailed comparison between Galileo's text on military architecture and Puccini's *Libro primo di fortificatione* of 1564 (Puccini 1990), reaching the convincing conclusion that Galileo's affiliation with the Florentine tradition is based mostly on what he learned from this text by Puccini (Bredekamp 2007b, 70–82; Lamberini 1990, 136–138). As a military architect, therefore, Galileo was a member of the circle of military engineers in Florence.[22]

---

[19] Reprinted in a commented edition in Lamberini (2007).

[20] For the practice among military engineers of collecting information from other engineers' manuscripts and presenting them as original proposals, see Lamberini (1987). Given the great exchange of manuscripts among military engineers during most of the sixteenth century and the practice of appropriating their contents, it becomes evident that Galileo's public charge of plagiarism against Baldassare Capra in 1607 represented quite an unusual event for their contemporaries. Indeed, this case testifies to the change in the social status of artist-engineers like Galileo, especially from the late sixteenth century on.

[21] Another mark of distinction is the way weapons are listed divided into categories defined by the weight of the balls the weapons shot. This point is considered in the next paragraph.

[22] One chapter of Galileo's treatise on fortifications is entitled: "On the *Quarto buono*. Instrument for the scarp" (*EN*, II:142). Special thanks to Thomas Settle, who, in a private discussion held in

The site of the fortress Another specific topic of sixteenth-century military architecture concerned the characteristics of the site where a fortress had to be built and the ways these characteristics could influence the design of the building. For example, a fortress on a rock was built according to principles and requirements which corresponded only in part to those valid for a fortress on flat terrain or on an island in a lake. The relevance of the setting in which the fortress had to be built became a canonical topic of treatises on military architecture thanks to the work of Florentine engineers around the mid-sixteenth century.

The status of Galileo's treatises The topics Galileo addressed in his two treatises on military architecture and fortifications were not new in Galileo's day, and he never presented them as if they were the result of new reflections. As far as their content was concerned, his lessons on military architecture must have been integrated closely with those on the use of the military compass,[23] as indicated by the high frequency of students who took classes on both of these subjects. His teachings on military architecture, along with, first, explanations of the functions of the military compass and, second, the exercises performed using the real instrument, constituted the nucleus of Galileo's activity as a private teacher.

Artillery Powered by Gunpowder

An officer at the end of the sixteenth century had to know how various pieces of artillery worked. Although Galileo never gave specific lessons devoted to this topic alone, such knowledge was transmitted in the context of the subjects of his other lessons. The analysis of the functions of Galileo's military compass back in the previous chapter showed that Galileo taught the use of the compass as a quadrant for bombardiers, the most relevant tool for artillerists. Yet the same compass could also be used as a caliber, an instrument that allowed the artillerist to calculate the quantity of gunpowder to be used, depending on the material of which the projectiles consisted.[24] During the lessons on military architecture, moreover, in the context of the question about how to position heavy artillery along the curtain of a fortress and on the bastions, Galileo furnished further relevant information about how to distinguish among different pieces of artillery.

Distinctions among sorts of artillery Galileo distinguished between artillery *reali* and *non reali*, respectively, those which shot balls heavier than eight libra, and those that shot lighter projectiles (*EN*, II:107; Lamberini 1990, 136). In fact, in his treatises on military architecture, Galileo affirmed a distinction among the various sorts of artillery that was traditional at the time and originated in the treatises of

---

Tenerife during the European Symposium on Galileo, first brought my attention to the relationship between Galileo's manuscripts on fortifications and the Florentine circle of engineers and military architects of the sixteenth century. See also Fara (1988, 235–236).

[23] The functions and the use of Galileo's compass were described in the previous chapter in the context of analyzing the activity of Galileo's workshop. See on pp. 29ff.

[24] The use of the compass as a caliber is explained in the previous chapter pp. 35ff.

Belluzzi and Puccini. Thus in this case, too, the close relation of Galileo's treatises with the Florentine circle of military engineers is confirmed. Many other treatises show the same distinction pointed out by Galileo, although most of them also list many sorts of weapons presented along with drawings and explanations concerning their use, whereas it seems that Galileo never composed such detailed descriptions.

On the use of artillery Although there is no further evidence directly demonstrating that Galileo occupied himself with the use and functioning of artillery powered by gunpowder in the context of his activity as a private teacher, an outline for a possible treatise (possibly another "unpublished treatise") has survived, which was completely dedicated to this topic.[25] Galileo's outline consists of 14 points (Fig. 3.11):[26]

> [1] Particular advantages of artillery over other mechanical instruments.
> [2] On its [the artillery's] force, and where it comes from.
> [3] Whether it [the artillery] works more powerfully from a certain distance or when it is close [to the target].
> [4] Whether the ball moves along a straight line, when it is not shot perpendicularly.
> [5] Which line the ball describes during its motion.
> [6] The cause and the time of the cannon's recoil.
> [7] Hindrances that make the cannon faulty and the shot insecure.
> [8] About loading them on the wagon and about taking them down.
> [9] On the manufacture of the caliber.
> [10] On the examination about the goodness and rightness of the cannon.
> [11] Whether the longer the cannon, the further it can shoot, and why.
> [12] At which elevation it shoots the furthest, and why.
> [13] That, when the ball comes back down perpendicularly, it does so with the same force and velocity with which it went up.
> [14] Several firing projectiles balls and lanterns,[27] and their use.

Artillery and Galileo's mechanics A closer analysis of Galileo's outline for a treatise about artillery shows that his intention was to write a text in which practical knowledge relevant for the bombardier would have been integrated with related

---

[25] The outline of this planned treatise is documented in Galilei (ca. 1602–ca. 1637, 193r). For an interpretation of this sketchbook in the context of the emergence of Galileo's mechanics, see Büttner et al. (2001).

[26] "[1] Particolari privilegii dell'artiglieria sopra gl'altri strumenti mecanici; [2] Della sua forza, et onde proceda; [3] Se operi con magior forza in una certa dist[anza] o da vicino; [4] Se la palla vadia per linea retta, non sen[do tirata] a perpendicolo; [5] Che linea descriva la palla nel suo [moto]; [6] La causa et il tempo dello stornare il pezzo; [7] Impedimenti che rendono il pezo difettoso et il tiro incerto; [8] Del metterle a cavallo e scavalcarle; [9] Della fabrica del colibro; [10] Dell'esamine circa la bontà et giustezza del pezzo; [11] Se quanto più e [è] lungo il pezzo più tira lontano, e perchè; [12] A quale elevatione tiri più da lontano, et perchè; [13] Che nel tornare la palla ingiù nel perpendicolo, torna con le medesime forze et velocità con che andò in su; [14] Diverse palle artifitiate et lanterne, et lor uso." Author's enumeration. In the manuscript the points 1, 2, 3, and 6 have been erased. For a comparison between Galileo's outline for a treatise for the artillerist and one by a military engineer, see for example Lorini (1609, 279ff), Tartaglia (1554, 37v) and Cataneo (1582), the latter being a complete treatise devoted only to this topic.

[27] Lanterns were also cylindrical gear wheels often used as components of machines. In this case, however, the term "lantern" means special projectiles able to set fire to the target, which were fired at wooden machines like the *tormenta*.

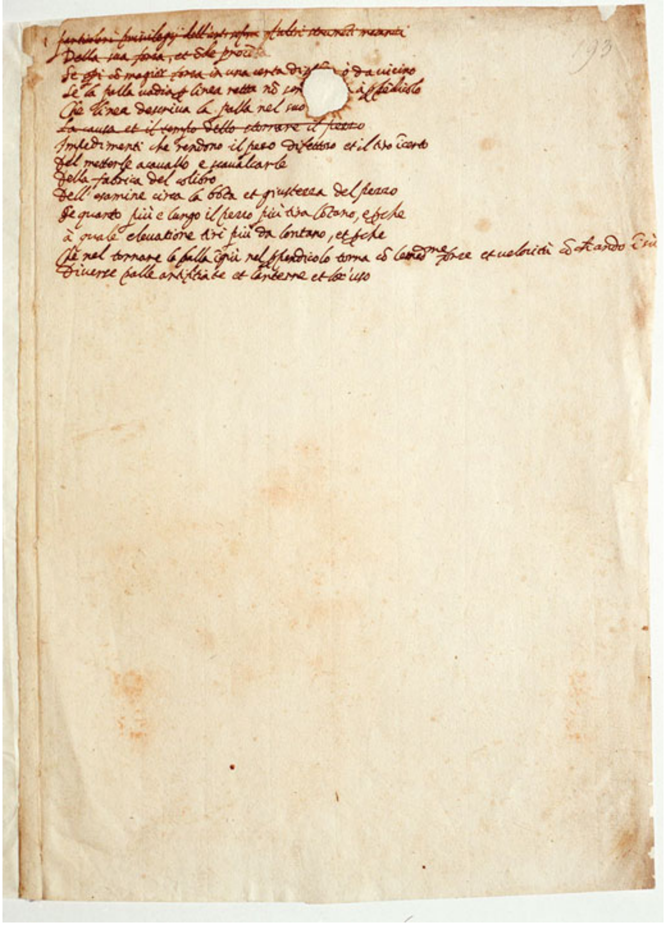

Fig. 3.11 Galileo's outline for a treatise on the use of the artillery (Galilei ca. 1602-ca. 1637, 193r)

theoretical speculations, which were particularly relevant in the structure of Galileo's theoretical mechanics. In particular, points 4, 5 and 13 are related to the development of his law of fall,[28] point 6 relates to Galileo's speculation about the force of the impact, as discussed in the Added Day of the *Discorsi* (*EN*, VIII:319–346). Points 9 and 12, finally, refer to additional operations which could be accomplished by means of Galileo's compass: the use of the caliber and the use of the quadrant for bombardiers, respectively, as described in the previous chapter.

The force of the shot The second point about the force of the artillery would probably have been a chapter dedicated to the composition of gunpowder, obviously

---

[28] On the relation between the artillerists' knowledge and the emergence of Galileo's law of fall, see Renn et al. (2001) and, more extensively, Damerow et al. (2004).

a relevant issue for those who had to assess its quality in order to load the cannon accordingly. The third point refers to a dispute *en vogue* in Galileo's day, as to whether cannons cause more damage when they are placed further away from the target or close to it. Galileo addressed this subject as well, in the context of his private and public lessons on military architecture.[29] In the tract used as a basis for his public lessons Galileo wrote:

> But first, before we go ahead, it seems a proper thing to me to speak a bit about a curious debate alive among some persons, who are expert bombardiers: which is, if it is better to place the artillery as close as possible to the wall that one wants to demolish; if, positioned at a certain distance away, it will have more effect than when positioned very close. And the reason for this discussion is that some believe and are completely convinced, that the artilleries will go through a thicker wall if they are positioned a certain determined distance away than if they were closer: This opinion, although it has endless proponents, can be nothing but false, and in a certain way ridiculous; as experience can make evident to anyone paying attention, and as reason can convince those who will think with right wisdom. In fact, since the motion of a ball is a violent motion, who will doubt that, once the ball is separated from its moving [force], it does not continuously lose its force? (*EN*, II:49)

Safety and cannon preparation Points 7 and 10 are about the quality of the piece of artillery and its possible imperfections. This kind of knowledge necessarily also included notions of melting and lathing procedures, and was obviously relevant for the safety of the bombardier and his assistants. Point 8 about the preparation of the cannons on the wagons concerns those machines which were required in every fortress, and which allowed the soldiers to prepare the artillery in case of attack, for they were not kept in defensive positions during peacetime. This issue will be discussed again later in this chapter.

La sfera

One piece of evidence that testifies to Galileo's lessons on *La sfera* are the entries in Manuscript 26 where he annotated the income he earned from his lessons. All of the entries are dated between 1602 and 1603, and all of the private lessons were given to Polish students.[30] The other and more important proof is the many copies still

---

[29] Galileo addressed the question of the distance between the artillery and the target in both of his treatises on fortifications. However, in the treatise identified as the one for the private lessons, he did so less extensively than in the one for lectures at the University of Padova. For the treatise for private lessons, see *EN*, II:118.

[30] Manuscript 26 documents private lessons on *La sfera* to twelve students, eleven of them between June 1602 and March 1603 and one in 1607 (Galilei 1598–1634, 149–158). University students normally attended courses on Euclid's *Elements* before starting lessons on *La sfera*. For a reconstruction of the curriculum of a university student at the end of the sixteenth century, see Favaro (1966, I:113).

preserved of a handwritten text attributed to Galileo and entitled *La sfera ovvero Cosmografia* (*EN*, II:205–209).[31]

The general topic of these lessons is specified at the beginning of this tract:

> We say thus that the subject of the cosmography is the world [...], which means nothing but *description of the world*. But we want also to point out that, of the things that could be taken into account in reference to this world, one part is the work of the cosmographer; and this is the speculation about the number and the distribution of the parts of this world, their figure, their size and their distance, and, above all, their motions; leaving the considerations about the substance and the qualities of the same parts to the natural philosopher. (*EN*, II:211)

The basic Aristotelian–Ptolemaic conception Galileo's text offers an overview of the conception of the universe, and accomplishes this task in accordance with the traditional views of his day. The universe explained in Galileo's cosmography corresponds to the Aristotelian–Ptolemaic system. The division of the universe into a sublunar and a superlunar world, the perfect circular motion of the firmament, and the central and immovable position of the Earth are the core concepts upon which this writing is founded. With this text Galileo followed the normal practice of lecturers on mathematics in his day. In fact, ever since the thirteenth century, books that exposed the Ptolemaic conception of the universe had constituted a very vital tradition that began with the *Tractatus de sphaera mundi* by Sacrobosco. Indeed, in this book written around 1240 in Paris, Sacrobosco described the motions of the celestial bodies according to the systems of Ptolemy and al-Farghânî (d. after 861 AD). The fame of Sacrobosco's book increased constantly until the end of the sixteenth century, when plenty of translated, annotated, and illustrated editions of it were in general circulation.[32] Typically, lessons on *La sfera* constituted the course of mathematics at the university during the sixteenth century.

The subjects of the *La sfera* treatises Besides the fundamental principles of the Ptolemaic conception of the universe, all of the commentaries to Sacrobosco's work address other topics as well. A later edition by Francesco Pifferi (1548–1612), a lecturer of mathematics at the University of Siena in 1604, describes how to measure the sizes of any body, how to measure distances between different places, how to recognize the winds and their relationship with the art of navigation on the sea, how to construct a solar clock, and how to find the center of gravity of a solid body. This knowledge was fundamental not only for the military arts and commerce, but

---

[31] William A. Wallace (1984b, 255–261) convincigly showed that Galileo's text *La sfera* was probably compiled using Clavius' homonym text (Clavius 1582) as fundamental work. For this reason, moreover, Wallace suggested that Galileo started working on his own *La sfera* during the years when he was working in Pisa as a lecturer of mathematics. This supposition, however, is not supported by any evidence.

[32] In an edition of the *Tractatum* of Sacrobosco published by Francesco Pifferi, a lecturer of mathematics in Siena in 1604, the editor had a difficult task in explaining why he published this book despite the fact that editions by famous scholars like Clavius, Maurolico, Alessandro Piccolomini (1508–1578), Magini, and Baroccio were in circulation at the same time. For more details, see his dedication to the readers in Pifferi (1604).

in general for anybody undertaking a long journey, like merchants, for example. Moreover, all of the treatises on *La sfera* contained a more or less complete outline of astrology, required by the university curriculum on medicine.

In his treatise, Galileo provided a table of the characteristics of each geographic area delimited by two parallels, though it did not consider only the seven Ptolemaic areas, but all twenty-two of the areas in early modern commentaries. The table published by Favaro, and attached to a copy of Galileo's *Trattato della sfera* preserved in Poland,[33] reports the following characteristics for each area: name, maximal duration of the solar day and a description of the changes in this duration, height of the pole of the celestial sphere, and length of the area. Finally, the data are given for each area in reference to both the northernmost parallel and the southernmost one, and with reference to the middle line between them.

Practical relevance of the lessons on Cosmography Galileo's private students copied this treatise and took lessons on it in order to be able to distinguish the celestial bodies. This then meant the acquisition of knowledge without which the use of instruments like the astrolabe, solar and lunar clocks, the armillary sphere, the astronomic quadrant and even Galileo's military compass would not make much sense. Indeed, only if the person operating such an instrument was able to recognize a celestial body was it then possible for him to determine, for example, the distance between the locations of the body observed at two different points in time. This further presupposes that the operator knows the motion of that body and, therefore, that he has a schema or conception which allows him to know the motions of all the celestial bodies. The same argument, then, is also valid for astrology and agriculture, for which Galileo taught the lunar phases.

The knowledge that Galileo taught in his private lessons on *La sfera* was generally useful to every military officer who needed to know such things as when night would fall, and also practical for merchants and even to diplomats. This was not the knowledge of philosophers, but rather that of officers and engineers like Boniauto Lorini.[34]

The Science of Machines

The last subject typical for a course on fortifications was the science of machines. During this course, students were supposed to learn enough to understand the functioning of machines relevant for the building and maintenance of a fortress, and

---

[33] Cod. 571, folios 2–45, Library of the University of Cracow.

[34] Given the aim of the lessons on *La sfera*, Favaro's hypothesis, that Galileo taught *La sfera* based on the conception of the Ptolemaic system only because he was afraid of possible repercussions from the Catholic Church, makes no sense at all (Favaro 1966, I:119–120). The only criticism that could be made against Galileo's text on cosmography is that it does not take into account all topics typical of treatises on *La sfera* at the time; for example, Galileo's treatise lacks any description of the winds, useful for navigation.

how to use them. When engineers and mathematicians approached this noble science, they rarely neglected to quote those ancient scientists upon whose reflections it was founded. Generally, Aristotle's *Mechanical Questions* (Aristotle and Hett 1980),[35] Archimedes' *Aequiponderantibus* (Archimedes 2002a) and the works of Hero of Alexandria, whose *Mechanics* was known via the homonym work of Pappus, were considered to be the works from which everything else originated. These works round out the framework of the ancient science of machines, upon which Renaissance mathematicians, engineers and machine makers founded their speculations and their imagination for new designs.[36]

The structure of the science of machines The science of machines of the Renaissance was structurally based on Hero's distinction among the five simple machines as he described them in the second book of his *Mechanica*, and as this structure was transmitted thanks to the *Mathematical Collections* of Pappus.[37] The simple machines were the lever, the pulley, the wheel, the wedge and the screw. According to this conception, the functioning of the five simple machines can be explained on the basis of the principle of the lever. All of the machines, finally, are either simple machines or compounds of two or more simple machines. The principle of the lever had been formulated first by Aristotle. This position was normally honored by Renaissance mathematicians, engineers and machine makers in the introductions to their treatises. In particular, Aristotle's introductory distinction between *Ars et Natura* (Aristotle and Hett 1980, 331), the former interpreted as products of the mechanical arts and the second as the products of nature, became a sort of *leitmotif* in publications by Renaissance artist-engineers.[38]

Early modern treatises on machines[39] Proceeding from the context of his activity as a private teacher, Galileo wrote not one, but actually two treatises about

---

[35] Up until the nineteenth century, the *Mechanical Questions* were ascribed beyond any doubt and with only one exception (Girolamo Cardano) to Aristotle. Nowadays the opinion prevails that this text was written by Aristotle's pupils. For more details see, Aristotle and Bottecchia Dehò (2000, 27–51). For a general introduction to Aristotle's *Mechanical Questions*, see Rose and Drake (1971), Gandt (1986), Laird (1986), Moletti and Laird (2000), Damerow et al. (2002), Büttner et al. (2003), and Valleriani (2009a).

[36] For an introduction to Pappus from the perspective of the history of mathematics, see Cuomo (2000). For a comprehensive work on ancient mathematics, see Cuomo (2001).

[37] The five simple machines are described in the eighth book. Pappus' work was translated and republished by Federico Commandino in Pappus Alexandrinus and Commandino (1588). In 1424 a manuscript of Pappus' *Mathematical Collections* was brought to Italy, where it is preserved at the Vatican Library today, MS. VAT. GR 218. Guidobaldo del Monte first brought Pappus to general attention during the Renaissance in Monte (1577). See in particular his dedication to Duke Francesco Maria II of Urbino. For an extensive discussion of Guidobaldo's revisitation of the works of Archimedes, Hero, and Pappus works, see Rose (1975, 230ff).

[38] During the early modern period, the Aristotelian distinction between *Ars* and *Natura* was interpreted differently by natural philosophers than by artist-engineers. This issue is discussed in Chapter 6, pp. 199ff.

[39] In the following a categorization of the early modern sorts of treatises dealing with the science of machines is proposed. This relevant topic is analyzed in this work only to the extent that is instrumentally required by the argument. For an extensive analysis of this topic, see Popplow (2004).

the science of machines, *Delle macchine* (Galilei 1592–1593a) and *Le mechaniche* (*EN*, II:145–191). In Galileo's day, moreover, the most important work on the science of machines was Guidobaldo del Monte's *Mechanicorum liber*, published first in Latin in 1577 (Monte 1577) and then in Italian in 1581 (Monte and Pigafetta 1581). Many other treatises were published as well. The most relevant were those that collected the descriptions and explanations of the relevant machines for living in a fortress, like Book 5 of Bonaiuto Lorini's *Le fortificationi*. Finally, other kinds of treatises also became very common and successful, including the "theaters of machines" and those treatises completely devoted to the analysis of one single machine. Examples of the last two sorts of treatises are *Novo teatro di machine et edificii* (Zonca 1607) of Vittorio Zonca (ca. 1568–1629) and *Tre discorsi sopra il modo d'alzar acque da' luoghi bassi* of Giuseppe Ceredi (Ceredi 1567).

Archimedes vs. Aristotle In his *Mechanicorum liber* Guidobaldo del Monte proposed a deductive system for the five simple machines such that, given some definitions and the principle of the lever, all of them could be rigorously deduced. As del Monte's aim was to furnish new theoretical foundations for the mechanical science, his work concerns only the basic definitions of the science of mechanics, the principle of the lever and the simple machines. In other words, not a single compound machine can be found in this treatise. Guidobaldo del Monte's work fully abandons Aristotle's *Mechanical Questions*, for it is based completely on Archimedes' definitions. In general, his *Mechanicorum liber* represented a rupture in the mechanical sciences because it was a sort of Archimedean attack against the Aristotelian approach (Bertoloni Meli 1992). As a consequence of Guidobaldo del Monte's publication, work on the Aristotelian *Mechanical Questions* entered a period of decline, until its role in the field of the science of machines finally became practically irrelevant during the second half of the seventeenth century.[40]

Engineers and Aristotle's *Mechanical Questions* Before and during the period when Guidobaldo del Monte published his *Mechanicorum liber*, engineers probably paid the greatest attention to the Aristotelian text.[41] Well-versed engineers like Ceredi, Zonca, Lorini, Giovanni Battista Aleotti (1546–1636), and Agostino Ramelli (ca. 1531–ca. 1600) quoted the Aristotelian text to explain their devices.[42]

---

[40] Guidobaldo, joining the old tradition promoted by Proclus and Plutarch, tried to defend Aristotle in his later publication, suggesting that Aristotle had offered Archimedes the idea on which he could work (Archimedes and Monte 1588). For Proclus' argument for Archimedes' mechanics compared to that of Aristotle, see Proclus and Friedlein (1873, 63). For the same topic in Plutarch, see *Vita Marcelli*, XIV:8. Del Monte displayed his familiarity with Proclus and Plutarch in his dedication to the readers in Monte and Pigafetta (1581). On the diffusion of the idea that Archimedes would be a "better" successor of Aristotle within the framework of the mechanical sciences, see Russo (2001). On the diffusion of the same idea during the early modern period, see Rose and Drake (1971).

[41] Aristotelian mechanics entered the university curriculum in Padova back in the sixteenth century. For a survey, see Bertoloni Meli (2006, 14). For an introduction to Guidobaldo's book and Aristotle's work, see also Bertoloni Meli (2006, 18–39).

[42] For a complete list of the translations of and the commentaries on the *Mechanical Questions* written by engineers during the early modern period, see Rose and Drake (1971, 97).

For example, it was an engineer who translated the *Mechanical Questions* into Italian for the first time in 1573 (Aristotle and Guarino 1573).[43] From the end of the fifteenth century on, Aristotle's work was published several times, first in Greek, then in Latin, then in Italian.[44] With each publication the text was adorned and expanded with more and more illustrations and commentaries. This process continued until the first half of the seventeenth century and more or less concluded with the commentary by Giovanni di Guevara (Aristotle and Guevara 1627).

Theaters of machines The aim of those engineers who were chiefly interested in compiling theaters of machines was in a sense opposite to that of mathematicians like Guidobaldo del Monte. In his *Novo teatro di macchine et edificii* (Zonca 1607), Zonca wrote not a single line of explanation on how simple machines work, but instead explained forty compound machines, complete with drawings and texts. As Zonca's text was for engineers, there was no need to explain again how the five simple machines work.

Didactic treatises Among these two opposite sorts of treatises on the science of machines were those compiled for a didactic purpose addressed to military officers. This is the case for Galileo's and Lorini's works, for example. This kind of treatise has a number of peculiar characteristics. First, they usually quote Aristotle's distinction between *Ars* and *Natura* as evidence of how mechanics is a science, which thus assigns men the role of dominating nature.[45] Second, they often refer to the principle of the lever as it was formulated by Archimedes. Third, they accept the theoretical structure represented by the definition of the simple machines, but then integrate this structure with issues relevant for the construction and actual uses of the machines themselves.

In fact, any of the simple machines was applied in many different ways, according to the purpose at hand and to the environment where the machine was supposed to work. As these applications were and are in principle not enumerable, most of the treatises written in the framework of officers' training open with a brief explanation of the principles of the five simple machines, and then continue by exhibiting a great number of illustrations of "real" applications of the machines.

Lorini's science of machines Bonaiuto Lorini dedicated one chapter of his treatise to the very specific topic of the machines of fortresses (Lorini 1609, 195–248). It starts with a historical introduction to the mechanical sciences. After mentioning Aristotle's distinction between *Ars* and *Natura*, the advantages that the mechanical

---

[43] Antonio Guarino was engineer for Duke Alfonso II d'Este of Modena. It was a tradition of the Este family to recruit engineers who also possessed a humanistic education. Another engineer of the Este family was Giovan Battista Aleotti, who translated Hero's *Pneumatics* into Italian in 1589. See also Palmieri (2003, 250).

[44] For a list of the Latin and Italian translations and commentaries of Aristotle's *Mechanical Questions* in the early modern period, excluding the late Renaissance, see the introduction to Aristotle and Bottecchia Dehò (2000, especially paragraphs two and three).

[45] The particualar view of the art-nature relationship according to which art dominates nature is normally ascribed to Francis Bacon (1562–1626). However, it has been shown that such an interpretation has its roots in the works of the artist-engineers of the end of the sixteenth century (Valleriani Forthcoming a).

sciences bring in wartime are shown first. Basing his argument on Archimedes' and Guidobaldo del Monte's works, Lorini then stated that all of the machines can be reduced to the balance and to the steelyard, and thus to the lever. Lorini then immediately provided the reader with five qualitative definitions useful for understanding how a lever works in practice—lever, force, horizon, axis, and radius—and follows them up with four propositions about the lever derived from Archimedes' *Aequiponderantibus* and Aristotle's *Mechanical Questions* (Lorini 1609, 195–201; Archimedes and Monte 1588; Aristotle and Hett 1980, 330–411). Lorini proceeded by explaining the main practical applications of the lever, that is, the simple machines, on the basis of which compound machines can be analyzed. The simple machines are the pulley, the wheel, the winch, and the screw.[46] The rest of the chapter closely resembles the kind of treatise known as a theater of machines. In this section Lorini describes a great number of compound machines and architectural elements that work on the basis of machines, including drawbridges and automatic doors.

Galileo's science of machines As mentioned, Galileo wrote two treatises on the science of machines: *Delle macchine* and *Le mechaniche*. These are two very different texts, though the second is certainly based on the first. Most of the subjects contained in Galileo's treatise *Delle macchine*, apparently an earlier version of *Le mechaniche*, are also presented in the later version. However, Galileo's method of argumentation changed significantly from one version to the next, revealing changes in Galileo's scientific interests. What is more, the first version also contains subjects that are not dealt with at all in the later one. According to Romano Gatto, the earlier treatise, *Delle macchine*, dates back to the years 1592–1593 and the later one, *Le mechaniche*, to the years 1598–1599.[47] A copy of the later version was first published by Marin Mersenne (1588–1648) in French in 1634, when Galileo was still alive, in the title of which Mersenne called Galileo *mathematicien et ingenieur* (Mersenne 1639).[48]

Galileo's *Le mechaniche* Galileo's later text on the science of machines, *Le mechaniche*, is one of the treatises written with the aim of supplying foundations for the science of mechanics, as was Guidobaldo del Monte's. This makes clear that the treatise *Le mechaniche*, usually considered only in the context of Galileo's

---

[46] Lorini did not consider the lever to be a simple machine, but a kind of fundamental tool to explain the machines.

[47] The treatise *Delle macchine* either has not been taken into account by historians, or has been regarded as a kind of poor summary of the later version *Le mechaniche* that does not show anything of interest in comparison with the second version. This interpretation was propagated by Favaro. For an outline of the discussion concerning historians' attention to the earlier version and for a detailed analysis of the differences between several copies of the two versions, see Gatto (2001, 2002). Romano Gatto transcribed, compared and finally published both *Delle macchine* and *Le mechaniche* in Gatto (2002), which offers an exhaustive analysis of these texts.

[48] Galileo's *Le mechaniche* was republished in Italian in 1649 by Luca Danesi (Galilei and Danesi 1649). No copy by Galileo's hand has been preserved. In *EN* Antonio Favaro listed eleven copies of the text in his *Avvertimento* to *Le mechaniche*. For bibliographic data, see *EN*, II:149–150.

emerging science of motion, was actually the further development of a part of a curriculum on fortifications. In the second part of *Le mechaniche*, the steelyard and the lever are explained first, followed by their applications, taking the form of axles in wheels and winches, pulleys, screws and Archimedean screws. The Archimedean screw is reduced not to the lever but to the model of an inclined plane;[49] there is also a final chapter entitled *Della forza della percossa* (On the force of percussion). No explanations of real or more complex machines is included in this treatise on mechanics by Galileo. Moreover, in this text Galileo approached the question of the relationship between products of the mechanical art and laws of nature, completely refusing to accept the view (his previous view!) that the science of machines would allow one to dominate, supersede or even defraud nature. Galileo noted that such a view was well established among artist-engineers, whom he thus criticized sharply.

Galileo's *Delle macchine* However, Galileo himself had been a strong supporter of the craftsman's view as well, which he taught to his pupils by basing his lessons on the earlier treatise on the science of mechanics, *Delle macchine*.

Four copies of the *Delle macchine* text have survived, designated by the names of the cities where they are now preserved. The one published by Favaro is in Ratisbon (Galilei and Favaro 1899); the second, discovered by Stillman Drake in 1955, is in Pasadena (Drake 1958), the third is in Hamburg (Galilei 1592–1593a) and the fourth, which probably belonged to Giovan Vincenzo Pinelli, is in the Vatican Library.[50] The Hamburg copy, which is the one considered here,[51] is contained in a folder labeled in an anonymous hand, in which the text is placed after a copy of a treatise on land surveying written in Early German.[52] After the copy of Galileo's *Delle macchine*, numerous treatises on military architecture follow. The first is a copy of Galileo's *Le fortificazioni*, used for his private lessons on military architecture. Some of the following treatises on fortifications are in Italian, some in Latin and others in Early German. A note at the bottom of almost all of the copies specifies that the copy was written in Padova. All of this taken together constitutes solid circumstantial evidence for the assumption that this folder was created by a German student, who took classes at Galileo's house for a certain period after 1592. The student probably also took other classes and used the opportunity of his stay at the University of Padova to collect as much material as possible relevant for the military and mechanical arts.

---

[49] For an exhaustive analysis of the relations between Galileo's treatment of the Archimedean screw, as expressed in *Le mechaniche,* and Galileo's theory of motion, see Galluzzi (1979, 199–227).

[50] For more details about the four preserved copies of Galileo's *Delle macchine*, see Gatto (2002, especially pp. CXLV–CLVIII).

[51] The following analysis of the Hamburg copy of Galileo's *Delle macchine* as well as the translated citations included in the present text, are performed on the basis of a transcription made by the author of the present work.

[52] The term Early German is not really exhaustive. The text is written in *Frühneuhochdeutsch*.

Art and nature in the *Delle macchine* In the very brief introduction to Galileo's *Delle macchine*, the text reads:

> The science of machines is that faculty that teaches us the reasons and gives us the causes of the *miraculous* effects that we see happen [...] about the movement of very great weights by means of a very small force.[53]

Galileo pointed out the contrary relation between *Ars* and *Natura*, as was usual for all the engineers or mechanicians of his time.[54]

After the introduction Galileo described the plan of the work:

> [...] we will start speculating from the first and simplest instruments, to which all the others reduce, or of which they are compounded, and they are called first instruments. First of all, there are the lever, the winch, the pulley, the screw and the wedge. All of which also reduce themselves, in some way, to only one, that is, the scales, or, the balance [...].[55]

The balance as the foundation of mechanics Galileo went on to introduce the case of a balance AB (Fig. 3.12), with a central support placed below the beam, and whose ends support two equal weights. Because of the equal distances between the ends of arm AB to the support, and because the weights are equal, the balance remains in equilibrium. This is clearly what Archimedes said in the first postulate of his *Aequiponderantibus*, and what is also written in many other introductions to treatises on machines of that time.

Still following Archimedes and, in particular, the second and the third postulates, Galileo then explained, first, how the balance loses its state of equilibrium, if either the weights or the distances from the support are unequal, or how it mantains the equilibrium if both are unequal in inverse proportion (Fig. 3.13).

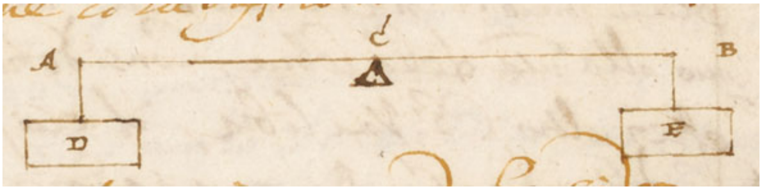

Fig. 3.12 Scale with equal arms supporting two equal weights (Galilei 1592–1593a, 15)

---

[53] "La scienza delle Machine è quella facoltà la quale c'insegna le ragioni e ci rende le cause, degli effetti miracolosi, che vediamo farsi [...] circa gli instromenti, circa il muover e alzar pesi grandissimi con pochissima forza" Galilei (1592–1593a, 15). Author's italics.

[54] Galileo's introductions to his *Delle macchine* and *Le mechaniche* are discussed at length on pp. 199ff.

[55] "[...] cominciaremo a specolare la natura dei primi e più semplici instromenti, ai quali gli altri si riducono, o di essi si compongono, e sono detti primi instromenti. In primero luogo c'è la Lieva. L'Argano. La Taglia. La Vite e il Conio. I quali tutti si riducono anchora, in certo modo, ad un solo, cioé, alla libra, ovvero bilancia [...]" Galilei (1592–1593a, 15).

Fig. 3.13 Scale with unequal arms and weights (Galilei 1592–1593a, 15)

After having clearly enunciated that such a balance stays in equilibrium when the relation between the weights is exactly the opposite of the relationship of the distances between the fulcrum and the ends on which the weights are suspended, Galileo stated that "this is the fundament of the whole mechanics, as will become evident as we proceed with the study of particular instruments" (Galilei 1592–1593a, 16).

The lever The second chapter approaches the topic of the lever in the strictest sense. Galileo began by indicating that the lever is an instrument everybody can see, and one that is used by all the masons. He then suggested considering the lever as if it were a balance, with the fulcrum the support on which the "stake of the mason lies." With the help of a drawing (Fig. 3.14), Galileo enunciated the principle for the lever in equilibrium: a lever is in equilibrium if the relation between the weights in B and D is the same of that between the distances between the weights and the support. In other words, there is an inverse relationship between the weights and the distances between these weights and the support.

The actual use of the lever A lever is used by the mason to move weights, not to keep them in equilibrium. Galileo followed this argument and therefore specified that it is sufficient to add a "minimal momentum" (Galilei 1592–1593a, 18) to weight B, meaning that, once the lever is in equilibrium, in order to move it, it is sufficient to add a weight so small that it must not be taken into consideration in the lever's construction. Any mason who would like to make a lever for himself needs

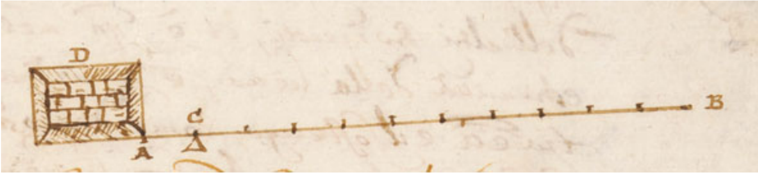

Fig. 3.14 Galileo's illustration of the principle of the lever (Galilei 1592–1593a, 17)

to know only the proportion between the weights and distances that will allow him to make a lever that remains in equilibrium.[56]

Galileo's principle of conservation Galileo proceeds by explaining the proportion between the movements of the moving weight, without that minimal momentum, and the moved weight. This inverse proportion is an important reminder that a lever with a moving weight, or force,[57] applied to the end of an arm, say, ten times greater than the distance between the support and the weight to be moved, also has to be moved a distance that is ten times greater than the space along which the moved weight would be moved. This means, finally, that a lever that uses a very small moving weight and, therefore, places this weight at the end of a very long arm, will need a longer time to accomplish its work than would a lever with a shorter arm and a correspondingly heavier moving weight.[58]

The winch and the axle in the wheel In the next chapter Galileo approached the winch and the axle in the wheel. These two machines are usually described in the opposite order. In fact, even if it is true that both the winch and the axle in the wheel are explained by reducing them to the lever, authors like Guidobaldo del Monte nevertheless preferred to explain the axle in the wheel first, and then the winch as an application of the former. Galileo started with the winch, and provided no hierarchically ordered explanation for the two instruments.[59] This could be seen as an evidence that the goal of *Delle macchine* was not the theoretical foundation of the mechanical sciences, but as simple as possible an explanation of each simple machine to which all the machines can be reduced.

In his discussion of the winch, Galileo took the vertical one into consideration. He presented a drawing reproducing the instrument as it could be normally seen, for example, on any building site (Fig. 3.15). Taking G as the middle point of the block around which the rope winds, the winch is reduced to the lever FGH, where the moving force is applied to F and the moved weight is in H. The proportion between force, weight and time of work, that is, the proportion between the force and the weight on the one hand, and the two parts of the arm on the other, is explained in

---

[56] Abandoning pure static reasoning in favor of the argument of minimal momentum would later bring Galileo into theoretical opposition with Guidobaldo del Monte. In fact, in his *Mechanicorum liber* Guidobaldo rejected treating minimal momenta, *insensibilia*, because they are not mathematically definable. However, at this step of *Delle macchine* the conflict did not arise, since this writing was not intended to provide any theoretical foundation for the lever, but only to explain what was important for the production, evaluation, and use of such machines. For Galileo's early reasoning on *insensibilia*, see Galilei (1592–1593a, 18); for Guidobaldo del Monte's, see Monte (1577, 43–44) and Monte and Pigafetta (1581, 39–40). For an extensive study on the concept of momentum in Galileo, and especially as concerns its development, see Galluzzi (1979, 199–206). For the relations between Galileo and Guidobaldo del Monte as regards the topic of the *insensibilia*, see Rose (1975, 233).

[57] Galileo interpolated the two terms "moving weight" and "moving force" for the same denotation.

[58] This argument is what Gianni Micheli called Galileo's principle of conservation. For more details, see in the previous chapter pp. 66ff.

[59] In the later *Le mechaniche* Galileo, too, inverted the order of the explanations.

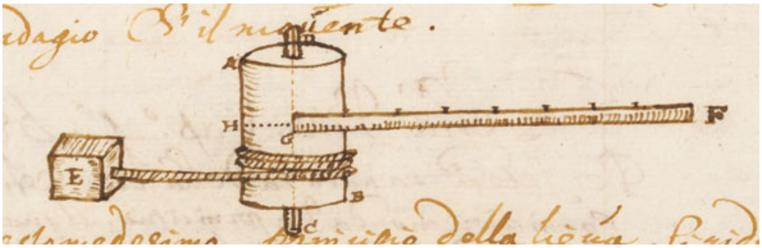

Fig. 3.15 Vertical winch (Galilei 1592–1593a, 19)

terms of "*facility* acquired by the force put in F" and "loss in time and velocity" to move the weight.[60]

The axle in the wheel is the same as the winch, where the block is an axle placed horizontally. In practice, since the block of the winch is vertical, the lever is moved by a horizontal arm, and the winch is thus more efficient when the force is applied by an animal walking around it. When the axle is horizontal and fixed in a wheel, necessarily vertical, this instrument is more easily operated by the force of a man. Of course this is true only if the machines are simple, that is, if no further transmission of the movements takes place. In his *Delle macchine* Galileo explained the axle in the wheel by means of a practical example represented by a drawing of a machine quite typical in Galileo's day (Fig. 3.16, left).[61] In particular, machines with this shape were used within fortresses, when it was time to prepare the cannons. Once the piece of artillery had been fastened and pulled up by operating the wheel, the wagon of the cannon was positioned under the axle and the cannon was lowered down onto it. For large and thus heavy pieces of artillery, there were two ways to make the machine capable of lifting that weight. One, also explained by Galileo, consisted in applying the axle to a wheel whose semidiameter is greater than that of the axle. Like the winch, the axle in the wheel can be considered as a lever, such that the moving force is applied at one point of the circumference of the wheel, the support is the line passing through the middle of the axle, and the weight to be moved is ideally located on the surface of the axle at a point opposite the point where the moving force is applied. The second way of making this simple machine more powerful is to apply a gear wheel instead of the wheel, so that the movement required by the moving force can be transmitted to such a position that the arm of the lever can be operated by an animal and thus with greater moving force.[62]

---

[60] Author's italics. In *Le mechaniche* Galileo gave the same explanation, stating that "the force acquires momentum equal to the resistance" (*EN*, II:170).

[61] Guidobaldo del Monte opened his chapter concerned with the axle in the wheel with exactly the same drawing (Monte and Pigafetta 1581, 102).

[62] In *Le mechaniche* Galileo abandoned this practical explanation for a geometrically more precise description of the change of the effects by changing the proportion between the semidiameter of the wheel and that of the axle (Fig. 3.16, right).

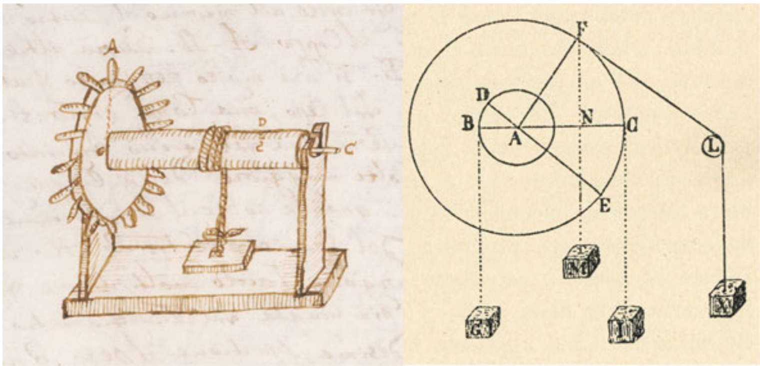

Fig. 3.16 Practical description of axle in the wheel on the left (Galilei 1592–1593a, 20) and geometrical illustration of the same instrument on the right (*EN*, II:167)

The screw As to the screw, Galileo took no pains to depict this machine in terms of the lever and balance as did, for example, Guidobaldo del Monte (Monte and Pigafetta 1581, 115–117). Galileo considered the helices of the screw as the surface of an inclined plane turned around a cylinder, i.e. the axle of the screw. The functioning of the screw is then explained in full by appealing to the behavior of a weight on an inclined plane. Although Galileo introduced his famous theorem of the inclined plane (Fig. 3.17) to explain how a weight moves along it, he did not provide any demonstration for this theorem, as he did later in *Le mechaniche* (*EN*, II:180–186).[63] Galileo pointed out that, on a plane parallel to the horizon, a ball would be moved by a minimal force and that this force has to be increased in proportion to the plane's elevation relative to the horizon. At this point he suggested skipping the "speculation" required to understand how much the force should be increased for any given elevation of the plane, and proceeded instead to the conclusion:

> [...] the weight has the same proportion to the force as the length of the elevated plane to the perpendicular height and thus, if we draw from point C the line CB, perpendicular to plane AB, the number of times that the length AC is greater than the height CB is the same number of times that the force sufficient to move the weight above the plane AC is smaller than the force that would be necessary to lift it [the weight] over the perpendicular AG [...].[64]

Galileo then quickly proceeded to approach the screw as an instrument to lift weights and, in greater detail, described a very famous, and useful, practical application of the screw: the "not only marvelous, but also miraculous" Archimedean

---

[63] Because of this theorem, Galileo entered in conflict with Guidobaldo del Monte, who provided for it a rigorous static demonstration. For more details, see Bertoloni Meli (2006, 35–39).

[64] "[...] il peso alla forza ha la medesima proportione che la lunghezza del piano elevato all'altezza perpendicolare, e cosi se dal punto C. tiraremo la linea C.B. perpendicolare sopra il piano A.B., quante volte tutta la lunghezza A.C. sarà maggiore dell'altezza C.B. tanto minor forza basterà per mover il peso sopra il piano A.C. di quella che sarebbe necessaria ad inalzarlo su per il perpendicolo A.G. [...]" Galilei (1592–1593a, 21). Galileo considered this explanation sufficient and did not even bother to remind the reader that the screw could also be conceived as a lever.

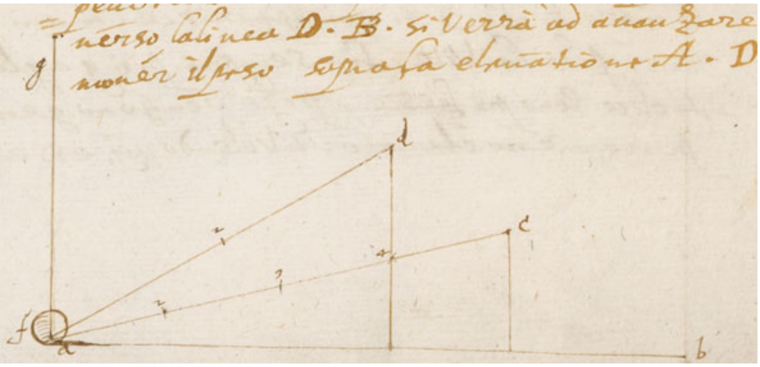

Fig. 3.17 Illustration of Galileo's theorem of the inclined plane (Galilei 1592–1593a, 21)

screw, that is, the machine to lift water. Galileo's clear, synthetic explanation considers every helix to be an inclined plane, whose angle of inclination to the horizon is always the same. If, in order to lift up water from one place to another, the screw is supposed to have an inclination of one fourth of a right angle, then the helices should have the same inclination in the opposite direction. This way the plane of the water would no longer be inclined, or even descending, so that the water which is lifted would actually follow a plane parallel to the horizon and thus the smallest of forces would be enough to move the water. Moreover, folio 21 exhibits marginalia concerning the threads of the screw and, in particular, the extent to which these threads should be hollowed and covered. These contrivances, which could be the results of further oral explanations, are not related to the theory of the instrument, but only to its efficiency when applied in practice.[65]

The pulley Finally Galileo proceeded to introduce the machine consisting of a system of pulleys. Corresponding with Guidobaldo del Monte, Galileo, too, explained at the beginning that a simple pulley works as a lever (Fig. 3.18). In particular, if it is placed over the moving force and over the weight to be pulled upwards, the arms of the lever are equal, thus establishing a perfect correspondence between the force and the "gravity" of the weight. Only a pulley placed under the moving force[66] is a lever with unequal arms, and therefore, given a certain force, able to lift weights greater than those lifted by simple force. In fact, the lower pulley corresponds to a lever, one of whose arms is the semidiameter of the pulley, and the other the whole diameter, i.e. one is double the length of the other. If a given force is able to sustain a given weight by means of a pulley placed over it, then the same force is able to sustain double the weight thanks to a pulley placed below it.[67]

---

[65] Practical contrivances related to building issues disappear in *Le mechaniche*.

[66] For more details, see the next section in this chapter.

[67] If the pulley is placed under the moving force, the weight cannot hang from the rope which turns around the pulley, but must be connected directly to the center of the same pulley, while the end of the rope where there is no moving force should be fixed somewhere else, like to a nail or a hook.

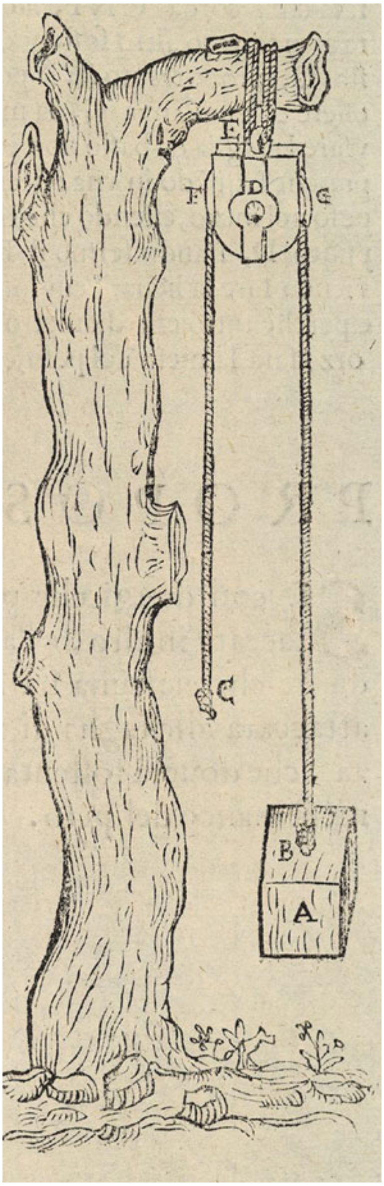

Fig. 3.18 Simple pulley explained on the basis of the principle of the lever (Lorini 1609, 201)

The third section of Galileo's *Delle macchine* The first part of the text *Delle macchine* is constituted of basic definitions and the explanation of the simple machines, just like Guidobaldo del Monte's work, for example. However, the character of this text is evidently more practical and not devoted to the foundations of mechanics. This conclusion is based on five issues. First, the Aristotelian introduction interpreted in such a way to remark on the dominance of mechanics over nature. Second, the simple machines are described not in the framework of a deductive system, but each as an independent issue. Third, the famous Galilean theorem of the inclined plane is mentioned only as a conclusion, with Galileo asserting explicitly that, for the purpose of the text, there is no need for its demonstration. Fourth, practical details, like those about the concavity of the helices of the screw to lift up water, clearly address the reader's attention to building issues. Finally, the text is followed by a series of examples of compound machines, as in Lorini's treatise. The last two parts of the manuscript, in fact, are, first, a series of exemplary combinations of simple machines in order to show how the force executed by a machine can be multiplied; and second, a series of examples of particular machines useful in the fortresses and their building details. The next two parts of this chapter will discuss these issues in detail.

Compounds of Simple Machines to Multiply Force

In his manuscript Galileo expatiated upon the many, in principle countless, possibilities of multiplying the effect of a given moving force, first in the single machines and then with reference to some typical and particularly efficient combinations of simple machines.[68]

Compound pulleys The system of two pulleys is introduced because the simple lower pulley would oblige anyone wanting to lift a weight with it to apply the moving force from the bottom up, that is, in a quite uncomfortable way. If a second upper pulley is introduced, the rope from the lower one goes around the upper one so that it hangs down where the hands of the workers could handle it easily (Fig. 3.19). For this reason alone, Galileo doubled the number of pulleys each time he showed increasingly efficient systems of pulleys. The principle is very simple: according to the relations between the weight, the moving force and the time to move the weight, every lower pulley allows the same moving force to lift double the weight, and every lower pulley should be accompanied by an upper one in order to allow the worker to work more easily. Together with this principle Galileo also presented a quick method to calculate how many times greater the "gravity" of the lifted weight can be than the gravity of the weight that could be lifted by the given moving force without any machine. One had only to count the "threads" of which the system is constituted, decrease this number by one unit, and the result is the number of times by which the given force is "multiplied" thanks to the given system of pulleys. As a matter of fact, this chapter of *Delle macchine* is better characterized as a collection of practical hints about the machine than as an explanation of its function.[69]

Uneven system of pulley In the later *Le mechaniche*, however, whereas all the practical hints disappear, Galileo extended the theoretical explanation of the

---

[68] Although Galileo promised to explain all the five simple machines, in neither *Delle macchine* nor *Le mechaniche* did he provide any sort of description of the wedge, which is one of them.

[69] On the basis of the explanation of the system of pulleys, Galileo also furnished a concrete example to show how the force is multiplied.

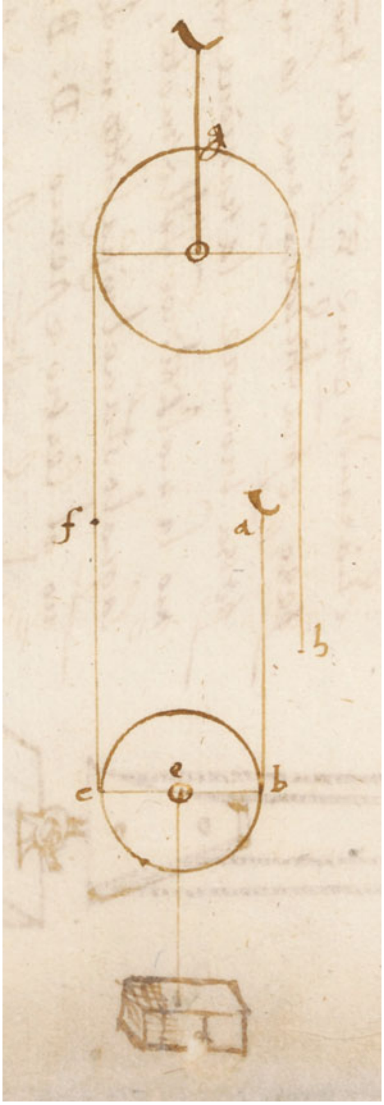

Fig. 3.19 Compound of two pulleys (Galilei 1592–1593a, 27)

machine constituted of pulleys by also taking into consideration what he called the “uneven” systems of pulleys. These systems differentiate themselves from the ones presented above because one end of the rope, rather than exiting from the lower pulley to be attached at some fixed position, exits from the upper pulley and is fixed to the lower one. In this manner the weight is sustained at three points: the two usual extremities of the diameter of the lower pulley, plus the point where the rope is fixed. In such a system a given force actually can sustain a weight three times heavier than in a system without auxiliary machinery.

Fig. 3.20 System of axles in the wheels (Galilei 1592–1593a, 30)

Compound system of axles in the wheel As to the axle in the wheel, Galileo first described how a compound system combining several of them can be constructed (Fig. 3.20):

> First there will be the axle [AB] around the center and pivot [B] and turned around this axle there is the rope, which sustains the weight. To turn this axle with less effort we fix the wheel [F] to it [...]. If we want to add another wheel, we will fix another axle, which, turned around, will make the wheel [L] turn and this will be done by meshing the gears to this [axle] and to the mentioned wheel [F]. Then, in order to make the [second] axle G turn easily, we will fix it to the second wheel [L], which, turned around, will make the axle turn [...], and finally, in order to move the last wheel [L] we will add another gear axle, or we could call it sprocket wheel [...], whose gears correspond to those of the wheel [L] and in order to turn this sprocket wheel [...] around, we will add to it a crank handle of iron [...] so that, when the hand is put on its handle, we can turn the sprocket wheel around with effort reduced to the same degree as the [semidiameter of the crank handle] is longer than the semidiameter of the sprocket wheel, because the [semidiameter of the crank handle], turned around, becomes the semidiameter of a circle or wheel described around [its middle] point, which, together with the sprocket wheel [...] constitutes the same instrument as the axle in the wheel.[70]

---

[70] The following description (Galilei 1592–1593a, 28–29) refers to a drawing in which space has been left free alongside the text, but was never filled. However, in folio 30 a drawing of exactly the same machine is given, using slightly different letters for the references on the figure. Reference letters therefore have been adapted. The original text reads: “Prima sarà l’asse A.B.C. intorno al centro e perno D.B. intorno a questo asse c’è avvolta la corda, che sostiene il peso, e per girare e rivolgere questo asse con minor faticha, vi innestiamo la ruota G.H.F.A. [...]. ma volendo noi agiungere un altra ruota, accomodaremo un altro asse; il quale girato atorno farà volger la ruota C.H.I. il che si farà col far i denti ad esso e alla ruota detta. Dipoi per poter volger l’asse G. con facilità, lo metteremo nella seconda ruota Q.H.L. la quale girata, menera in volta l’asse G. [...], e finalmente per mover l’ultima ruota H.I. l’aggiungeremo un’altro asse dentato, o vogliamo chiamar rocchetto M.N. [...] e per menar atorno questo ultimo rocchetto M.N ci vi aggiungeremo il mangano di ferro O.P.Q.R. di [...], che posta la mano nel manico Q.R. volgeremo con tanta minor fatiga il rocchetto M.N. quanto la linea P.Q. sarà maggiore del semidiametro del rocchetto, perche la linea P.Q. girata intorno, diventa semidiametro d’un cerchio o ruota descritta dal punto Q. la quale con il rocchetto M.N. fa il medesimo instromento, che l’asse nella ruota.”

Given the instructions for how to make such a machine, Galileo proceeded with a concrete example of a machine constituted of three axles and three wheels (Fig. 3.20). If the first wheel F, to which the axle around which the rope winds is attached, has a semidiameter five times greater than that of the axle, and if, in reference to the second wheel and its sprocket wheel, the semidiameter of one is one four times greater than the other, and, finally, if the semidiameter of the crank handle is three times longer than that of the next smaller sprocket wheel, then a given force will be able to move a weight which is 5 × 4 × 3 = 60 times heavier than the weight which the same force would be able to move without the help of the system of wheels (Galilei 1592–1593a, 29). However, at this point Galileo did not neglect to introduce a calculation which demonstrates accurately that, if the increase in efficiency of the machine corresponds to a multiplication of the given moving force by 60 times, this means that the space along which the force is transmitted is 60 times longer, that is, that the time to move the weight would be 60 times longer than if the weight were moved by a force 60 times greater but without the auxiliary machine.

Compound of axle in the wheel, screw and winch Galileo then presents a similar way of proceeding to a compound of three different simple machines, a machine to lift weights: axle in the wheel, screw and winch (Fig. 3.21). This typical machine was called a perpetual screw, where perpetual refers not to perpetual motion, but means that the motion of the machine is mechanically not restricted to a range between two end points. In fact, the axle in the wheel corresponds to the axle D, which is fixed to the wheel ABC. The given moving force is multiplied in this machine according to the relationship between the semidiameters of the axle and the wheel. By means of gears around the wheel, then, the axle in the wheel can be assembled to the screw. For example, if the length of the distance along which the weight has to be moved is divided into ten helices, then the given moving force is multiplied by ten (Galilei 1592–1593a, 31). This means that the degree to which a

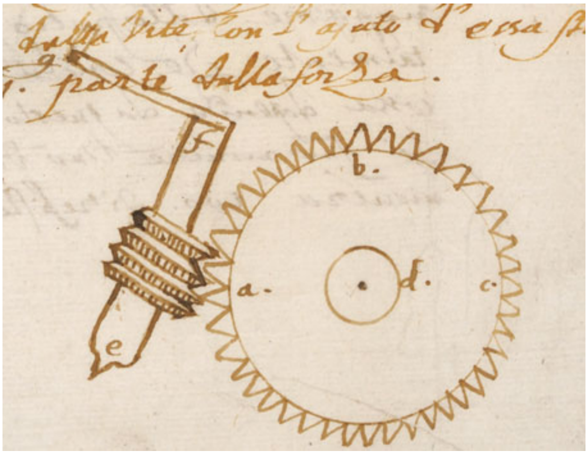

Fig. 3.21 Compound of axle in the wheel, screw and winch (Galilei 1592–1593a, 31)

composition of screw and wheel helps the worker depends on the number of helices on the screw in a given space along its axle. The more helices there are, the more the force is multiplied.[71] Finally, there is the winch, which works as an axle in the wheel and corresponds to the crank handle of the machine. Galileo concluded that, if the semidiameter of the wheel ABC is five times longer than that of its axle, and if the screw multiplies ten times, and, finally, if the semidiameter of the crank handle is four times longer than the semidiameter of the axle of the screw, then the given moving force is multiplied $5 \times 10 \times 4 = 200$ times.

The actual treatise *Delle macchine* closes with a discussion about the force of percussion.[72] To determine how much force a stroke can generate was important for engineers, in constructing machines like pile rams, for example. Such machines were required on building sites, in particular, and especially on those where a fortification of earth had to be built. Galileo explained that the stroke follows the usual mechanical principle which relates the force, the distance along which the force is moved, and the weight, which, in this case, corresponds to the resistance of the object that receives the stroke to be moved.

Compound Machines Useful in the Fortress

Galileo himself stated in his outline for the course on mathematics for the *Accademia Delia* that students have to gain "Knowledge of the mechanical sciences, not only about their reasons and common basis, but also regarding many machines and particular instruments." The third section of the manuscript fills this gap. In the copy preserved at the Staat-Universitätsbibliothek of Hamburg, the treatise *Delle macchine* is followed by thirteen folios on which different machines and their details are drawn. Some of these drawings also have captions written by the same hand that copied Galileo's treatise and wrote the notes on its margins.[73] It can therefore be supposed that either the earlier version *Delle macchine* generally was provided with these drawings, or that further discussions on particular machines took place during private lessons at Galileo's home. This second hypothesis seems more probable as these drawings were hardly new or unfamiliar, but rather familiar drawings, which had been studied and analyzed by a great many engineers and machine makers in Galileo's day. They are drawings of machines designed by the famous engineer Francesco di Giorgio Martini (1439–1501).[74]

---

[71] The more helices there are along the same section of the cylinder, the smaller the gears of the wheel have to be.

[72] The last folio of *Delle macchine* is entitled *Della forza della percossa*. This short text exhibits only minor differences from the one published by Favaro at the end of the later version *Le mechaniche* (*EN*, II:188). For a comparison between the structures of the texts of the four preserved copies of Galileo's *Delle macchine*, see Gatto (2002, CLI).

[73] Most of the notes and all of the captions are written in Early German. The collection of drawings is followed by a copy of Galileo's treatise on military architecture.

[74] Thanks to Marcus Popplow for helping me with the first approach to these drawings of machines.

Francesco di Giorgio Martini “Master Giorgio” was born in Siena in 1439. He was a painter, sculptor, architect and engineer, who worked mostly in Siena and in Urbino. Author of many architectural works in these cities, he also compiled notebooks with drawings of machines for many purposes throughout his lifetime. He finally wrote his famous *Trattato di architettura civile e militare* in Urbino, probably in 1481 (Giorgio Martini 1967), one year before his death on the field near Ferrara. Martini’s *Trattato* and notebooks were quite well known throughout the Renaissance. Copies of his drawings can be found in a great many treatises by other authors, and many anonymous manuscripts of that period. Not only in Siena and Urbino, but also in Naples, Rome and Venice, Florence, Martini’s drawings of machines constituted the first point of reference for all engineers. Reminiscences or even exact copies of Martini’s drawings can be found, for example, in the treatises of Bonaiuto Lorini, Vittorio Zonca, Oreste Vannocci Biringucci (1558–1585, nephew of the famous Vannoccio Biringuccio), Agostino Ramelli and Jacques Besson (1540–1576).[75] At the Biblioteca Marciana of Venice, an annotated copy of Martini’s treatise is preserved, bearing a bookplate with the inscription “Organa Mechanica Gui. Ub. ex Mar. Mon,” that is, which belonged to Guidobaldo del Monte,[76] Galileo’s patron. There are many other indications suggesting that Galileo knew Martini’s work as well, not only because the engineer Zonca was active in Padova during exactly the same years as Galileo, or because Guidobaldo del Monte owned Martini’s treatise. As a matter of fact, Martini’s drawings were so well known that one could even say that they belonged to the common imagery, as demonstrated in the ludic competition that took place in the waters of San Marco on October 23, 1530. On that occasion the masters of the Venetian Arsenal actually erected a wooden castle above two platform boats, clearly evoking Martini’s typical machinery (Sanuto and Fulin 1969–1970, LIV:col. 79–80).

The machine drawings in the manuscript All of the drawings in the Hamburg manuscript are of machines whose mechanical parts are set into a box, which is a typical characteristic of Martini’s drawings of machines. In general they are compositions of winches, wheels and screws. Most of the twenty drawings of machines in the Hamburg copy can be easily identified in Martini’s *Trattato di architettura*, some of them reproduced exactly and others with some variations. The rest of the drawings of machines were copied from Martini’s *Opusculum de architectura*. This notebook, dated by Paolo Galluzzi to the years between 1475 and 1478,[77] is considered to be Martini’s second notebook of drawings and was catalogued at the Biblioteca Ducale of Urbino until 1722, when it was brought to England (Giorgio Martini 1475–1478). Ultimately there was only one drawing that could not be identified with any other drawing by Martini or by other engineers.

---

[75] Lorini (1609), Zonca (1607), Vannocci Biringucci (after 1562), Ramelli (1588) and Besson (1578). For a reconstruction of Martini’s influence during the Renaissance, see Reti (1963).

[76] Ms. Lat. VIII 87 (3048), Biblioteca Marciana, Venice.

[77] Paolo Galluzzi considers the problem of dating this notebook to be objectively insoluble. For a complete overview about this notebook, see Galluzzi (1991, 203).

The function of the drawn machines Apart from one pile driver, one millstone and one water-lifting pump, all of the remaining drawings represent devices to lift weights. No machine requires running water or wind as a moving force; all of them are conceived to be operated by either men or animals. This selection thus shows a particular interest in machines that were especially useful on construction sites. And since the approximately 500 folios of the manuscripts remaining are copies of treatises on fortifications and military architecture, one can presume that the goal of this collection of drawings is to report on the machines which could be useful both on the site where a fortification was being built, and to complete the various tasks typically needed by the residents of such a place.

Compound machine to lift weights (1) The drawings represented in (Fig. 3.22) are exact copies of Martini's drawings of machines to lift weights.[78] Both machines operate by means of a lever or crank handles that can be inserted at the top of an axle, along which there is a screw. In the machine on the left, the screw operates on a gear wheel, the lower part of which is connected to a lantern positioned horizontally along an axle. Finally, a rope, which is tied to the machine at one end, winds around the latter axle, with the weight suspended from its other end. The lifting machine on the right is a variation of the first one. The wheel operated by the screw in this machine, which can lift two weights simultaneously, has an axle along which there

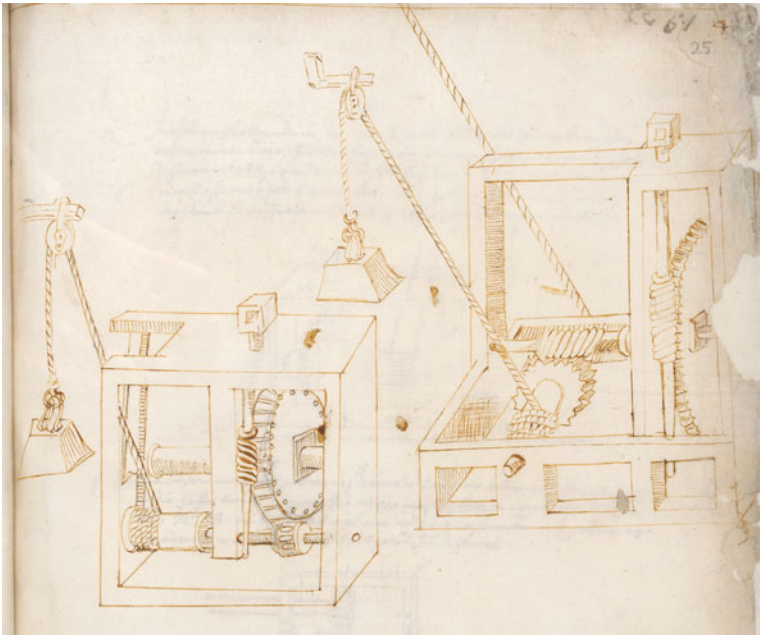

Fig. 3.22 Machine to lift weights constituted of a crank handle, a screw, a wheel, an axle, a pulley and a lantern (Galilei 1592–1593a, 51)

---

[78] Ms. Cod. Math. 200b, Hamburg, folio 51. These drawings are copies of Giorgio Martini (1475–1478, 4r).

is a further screw that is connected with a double axle in the wheel. As the drawings clearly show, these machines could be expanded by connecting a pulley or pulley system. Connecting such additional machines not only improved the efficiency of these devices, but also made it easy to adapt them to the practical context of each given construction site and to the particular requirements of the given workflow.

Compound machine to lift weights (2) Some of the drawings of machines of the manuscript preserved in Hamburg are drawn first in large format on a whole folio and then, some folios later, in a smaller size but accompanied by the drawings of the simple machines of which the first is constituted. This is the case, for example, for the lifting machine illustrated in Fig. 3.23, which is also an exact copy of a drawing by Giorgio Martini.[79] The prime mover of this device is a winch that is operated by a multiple crank handle. Depending on the dimensions of the device, such a machine can be operated either by men or by animals. The winch, a simple version of which is drawn in the middle, is connected to an axle in the wheel by means of two gear wheels. The axle in the wheel, drawn on the right, is represented here by an axle, around which the rope winds, and by a crank handle, whose vertical component corresponds to the wheel.

Positioning artillery onto wagons One of the chapters listed in the outline of the treatise mentioned earlier in this chapter, entitled "Particular Advantages of the Artillery in Comparison with other Mechanical Instruments," (Galilei ca. 1602–ca. 1637, 193r) deals with the operation of positioning artillery on wagons inside a fortification. This task was indeed a very important one. As Lorini told, great effort was spent to organize the fortifications so that this operation could be accomplished as quickly as possible. The soldiers also had to be drilled for it and, obviously, extremely efficient lifting machines were required. Galileo's potential chapter thus touched a nerve center for everything concerned with a fortification. This topic involved questions about the defense strategy of the fortification, such as where the artillery room should be located and how long the whole operation should take,

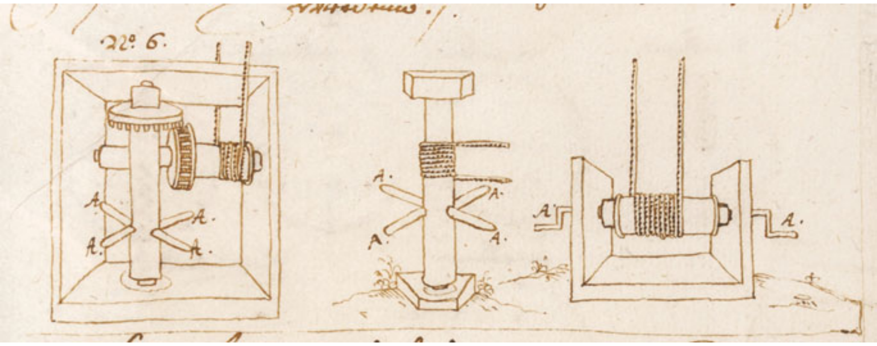

Fig. 3.23 Machine to lift weights constituted of a multiple crank handle, a winch and an axle in the wheel (Galilei 1592–1593a, 56)

---

[79] Ms. Cod. math. 200b. Hamburg. folio 56. These drawings are copies of Giorgio Martini (1967, f. 51, Table 93).

and, again, with how many machines and which ones the fortification should be equipped.

Compound machine to place cannons onto wagons For this purpose a complex machine is depicted among the drawings of the Hamburg manuscript (Fig. 3.24). What is peculiar about this drawing is that it is not a copy from Martini's treatise or notebook. In fact, this machine and its representation seem more modern that those of Martini. The device is constituted of a winch as a prime mover, which can be operated either at the top or at the bottom, and of a first lantern along the winch, further connected with a gear wheel in the middle. This gear wheel drives another lantern that has internal threads for a perpetual screw, which is not supposed to turn, but only to ascend or descend. The solution of a perpetual screw that does not turn is already present in Martini's treatises, but there it is always a mother screw positioned above the machine, in direct contact with the surface through which the screw ascends. The constitution of the machine drawn in the Hamburg manuscript, therefore, appears to be an attempt to decrease the effect of friction. The peculiarity of this solution is also shown by the attention paid to it by the author of the drawing. The three drawings on the left, indeed, illustrate how this part of the machine works. From right to left, the first cutaway shows the longitudinal section of the second lantern with its internal threads, the second demonstrates that two hollows have to be made along the screw and that the screw has to go over another small component illustrated in the third horizontal section. This last small component is a small pivot, which fits with the hollow of the screw and prevents it from turning, allowing only vertical motion.

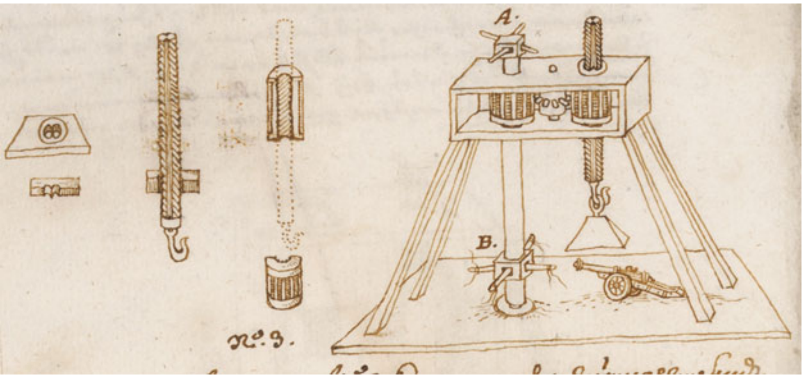

Fig. 3.24 Compound machine to prepare heavy artillery (Galilei 1592–1593, 55)

The Art of War and the Materiality of Machines

To ensure the success of his enterprise, Galileo had to make contacts outside of university life. His house, crowded with people, and housing a workshop for mathematical instruments, was not merely a meeting place for craftsmen like smiths, with whom Galileo performed systematic work, but also a sort of training camp for future military officers.

Galileo integrated the practical knowledge he acquired from the Florentine circles of military engineers and architects together with his experience as a designer and producer of mathematical (military) instruments and, finally, also with the practical arithmetic, geometry and mechanics that he learned from Ostilio Ricci during his youth. The result of such an integration of knowledge was a complete overarching course on fortifications typical of the military engineers of the second half of the sixteenth century.

Galileo's apprenticeship, his activity as an instrument designer and workshop manager and, finally, his copious teaching activity, demonstrate strongly how Galileo's profile was that of the artist-engineer, who, in keeping with the trend of the sixteenth century, tried to place his work within the framework of the early modern art of war. Until the end of 1609, when Galileo suddenly and unexpedectly turned the telescope toward the sky, he worked and was perceived primarily as a military engineer.

Engineers and military architects like Galileo were not the ones who built machines, but they were often the ones who oversaw their construction or evaluated them. However, Galileo's knowledge of mechanics, as can be inferred from the content of his private course on fortifications, does not seem sufficient for those tasks: To oversee the construction of a machine or to evaluate it, the materiality of the machine itself had to be taken into account. Issues like thickness, robustness, and the enlargement of devices from the scale of a model up to a real machine were part of this knowledge. As Lorini added:

> And since the demonstrations, and the propositions among the superficial lines, and the imagined bodies, and separated from the matter, do not properly work, when they are applied to the material things, that is, that the mental concepts of the mathematician do not receive and are not affected by those hindrances, that the matter always entails by its nature, and with which the mechanician works. [...]. Therefore, for the mentioned things, I will remind all of those, who would like to engage themselves in such enterprises such as judging or leading the execution of whichever machine, that it is necessary not only to have knowledge of mathematics, but also to be a shrewd and experienced mechanician [...].[80]

The insights presented in Galileo's private course on fortifications, related to his activity as an instrument maker, show that he shared manifold aspects of the practical knowledge, but did not reflect much on the materiality of the machines. Nevertheless Galileo, too, completed Lorini's training program to become what Lorini called a "mathematician–mechanician." He did so at the Venetian Arsenal, whose knowledge became the fundament of his First New Science, namely the science of the strength of materials. This is the topic of the next chapter.

---

[80] "E perche le dimostrationi, e proportioni, che si ritrouano tra le linee superficie, e corpi imaginarij, e separati dalla materia, non rispondono cosi esquisitamente, quando alle cose materiali si applicano, cioè che i concetti mentali del Matematico non riceuono nè sono sottoposti a quegli impedimenti, che di sua natura sempre porta seco congiunti la materia, con che opera il Mecanico; [...] Adunque per le cose dette ricorderò a quelli, che si vorranno porre a così fatte imprese nel giudicare, ouero comandare l'essecutione, di qual si voglia machina, esserli necessario non solo hauer cognitione delle Matematiche, ma ancora essere aueduto, e pratico Mecanico [...]" Lorini (1606, 196).