Chapter 4
The Knowledge of the Venetian Arsenal

Galileo crossed the threshold of the Venetian Arsenal in 1593, where, thanks to the mediation of its executive body, he came into contact with shipwrights and oar makers. Later in his career Galileo opened up a new field of modern science, one concerned with the strength of materials, thanks to the publication of the first of his two new sciences in the *Discorsi e dimostrazioni matematiche intorno à due nuove scienze* (*EN*, VIII:39–318).[1] These two events in Galileo's life are intimately connected: Galileo's first new science is rooted in the practical knowledge of the shipwrights of the Venetian Arsenal, the high-tech center of the Republic of Venice.

Politically, sixteenth-century Venice was characterized by the development and accession of a party known by the moniker "Of the Youth." Its ambition to occupy prestigious offices in the Venetian political system was related directly to its members' perceived need for cultural emancipation through studies, first, of ancient knowledge according to the humanistic spirit, and, second, of practical knowledge related to the needs of contemporary Venetian society. Necessary were (a) the knowledge of a military architect, because the fortifications on the mainland required a complete reorganization. This was a consequence both of the increasing tendency of the Venetians to address their life to the mainland, and of the development of heavy artillery; (b) the knowledge of a *Proto dei marangoni*, a shipwright of the Venetian Arsenal, because of the need to potentiate and therefore renew the Mediterranean fleet, which was itself a consequence of the growing power of the Ottoman fleet and the increasing presence of pirates; (c) the knowledge of a civil architect, because of the need for architectural changes to the city of Venice in order to pay tribute to the greatness and affluence of the Republic and its empire. In other words, the new needs of Venice represented new practical challenges, and the knowledge required to accomplish them was thus also practical. This cultural turn became increasingly relevant starting back in the early sixteenth century: The *Doge* Loredan, for example, had himself portrayed as bowing while offering to St. Mark the project of the reconstruction of Rialto (Concina 1990, 37). In 1517 Andrea Gritti was elected *Doge* of the Republic after having presented a plan to renew all of the

[1] On the development that proceeded from Galileo's first new science up to a complete classical theory about the behavior of materials, see Szabó (1987, 351–402).

M. Valleriani, *Galileo Engineer*, Boston Studies in the Philosophy of Science 269,
DOI 10.1007/978-90-481-8645-7_4,

fortifications on the mainland (Concina 1990, 47–48). The rediscovery of ancient wisdom was related directly to the great architectural, mechanical, technical—in a word: practical—challenges, and to the knowledge they required. During the sixteenth century, it was proposed to build a public library on the square of Venice that was dominated by the Byzantine library of Bessarion. In the words from the first oration of the renowned Venetian humanist Vettor Fausto (1480 ca.–1546), the library would have been a casket of the "secrets of venerable Antiquity" (Fausto 1551, 31r), while Fra Giocondo, the lauded translator of Vitruvius' *De architectura*, presented a proposal for reconstructing Rialto's marketplace in the form of a Greek *agora* (Vitruvius et al. 1513; Concina 1990, 39).

The principle according to which ancient and practical knowledge had to be directly related to each other also led to the decision of the Venetian Senate and the *Collegio della Repubblica* at the beginning of 1526, to commission the Arsenal with the construction of three ships much larger than the usual size. The Senate's intention was to carry out tests on the three ships to investigate several of the problems normally exhibited by the Venetian galleys, such as insufficient maneuvrability in the absence of wind, for example, and a lack of stability when equipped with new heavy artillery. As usual in Venice, the *Collegio della Milizia da Mar* then had to assign the task of constructing the ships to three masters of the Arsenal. This sort of assignment generally was decided not only by representatives of the political and administrative bodies, but also by a variety of masters and other foremen, according to their specialization. The aspiring headmasters had to be ready to present and defend their projects, not only through debate, but also with drawings and models. A discussion lasting over a year resulted in the following assignments for the three test galleys: the first ship to the brothers Matteo and Leonardo Bressan, and the second to Francesco di Todaro, all of whom were famous and experienced masters of the Arsenal at that time. For the third ship the above-mentioned Venetian lecturer in Greek, Vettor Fausto,[2] was chosen. Fausto, who was famous in the intellectual circles of Venice for his philologically accurate translation of Aristotle's *Mechanical Questions* completed in 1517, proposed to the Venetian Senate the construction of a *quinquireme*, whose design was based, he claimed, on the study of the ancient Greeks (Aristotle and Fausto 1517).[3] The Senate granted Fausto free hand to work in one of the Arsenal's typical Venetian shipyards, known as a *squero*, and assigned to him a team of specialized shipbuilders. This was the first documented instance of an intellectual going into a workshop with the purpose of working together directly with professionals of one specific art. In the words of

[2] Archivio di Stato di Venezia, Senato Mar, reg. 21, c. 24. September 29, 1526.

[3] The decision to commission Fausto with the building of a galley and to assign him a shipyard was the output of a convoluted process, which is documented in the diary of Marino Sanuto, a sixteenth-century Venetian nobleman. See in particular: Sanuto and Fulin (1969–1970, 39, col. 322). Aristotle's *Mechanical Questions*, translated by Fausto himself in 1517, address questions concerning ship design as well. In particular, see problems four, five, and six: Aristotle and Hett (1980, 355–361). See also pp. 132ff in this chapter.

Fausto, as he related his experiences about the Venetian Arsenal to his friend Giovan Battista Ramusio (1486–1557), when he went into the *squero* it was like a descent into Hades: "through grottoes shaped by scabrous rocks leaning askant, there, where the tremendous thickness of the subterranean darkness reigns."[4]

Galileo entered the same darkness Fausto did. After completing a sort of training program, he was then able, at long last, to shape part of the knowledge of the shipwrights of the Venetian Arsenal into a more general deductive form. This is what then became the first of his two new sciences: the science of the resistance of materials.[5]

Galileo's science of materials is revealed in the first two Days of his *Discorsi*, and based on three models. The first, the aim of which is to find the resistance to fracture of solid bodies stressed along their longer axis, is called here the rope model. The second is the cantilever model, constituted of a prism or cylinder placed parallel to the horizon and driven into a wall at one of its extremities. The purpose of this model is to find the resistance to fracture along the shorter axis of a solid body fixed to another one. The third, which might be called the "oar model,"[6] resembles the second model, except for the condition that the body is not fixed at one of its extremities to another body, but lies on it at one or more different points, like, for example, a column that rests on a certain number of supports on the floor.

First, Galileo's cantilever model will be analyzed with reference to those aspects which were most relevant for craftsmen such as machine makers. Second, the theoretical model of the same craftsmen concerned with the resistance of materials, as it was commonly explained around the beginning of the sixteenth century, will be described in terms of its Aristotelian origins. Given these two opposite approaches to the discussion, it will be shown how Galileo, also intellectually equipped with Aristotle's *Mechanical Questions*, visited the Venetian Arsenal. It will be shown that the practical knowledge he shared with the Venetian masters, especially with regard to some of the problems upon which Aristotle himself had focused, made Galileo such an expert on nautical issues that he actually became involved in management, working with the executive body of the Arsenal itself. The knowledge that Galileo acquired thanks to this experience served as the basis for his formulation of the cantilever model. Finally, this chapter concludes with an attempt to furnish the historical context from which Galileo's oar model emerged.

---

[4] "[. . .] attraverso grotte formate da scabre rocce strapiombanti, là dove regna il tremendo spessore delle tenebre sotterranee [. . .]," from Fausto to G. B. Ramusio, 1530, in *Epistolae clarorum virorum* . . . 1586, 128–133. For the importance of this event, see also Concina (1990, 46–70).

[5] As a result of an analysis of some of the sources considered in this chapter, the connection between Galileo's science of the strength of materials and the practical knowledge of the Venetian Arsenal was first described in Renn and Valleriani (2001). Back in 1976, moreover, Thomas Kuhn suggested investigating in such a direction to understand the emergence of Galileo's first new science (Kuhn 1976, 56).

[6] The oar model is discussed on pp. 150ff in this chapter.

Dating Galileo's Work on the Science of Materials

In a letter sent by Galileo to Antonio de Medici on February 11, 1609, in which Galileo discussed his return from Padova to Tuscany, he related his latest scientific results and those he wished to achieve. Among the known results, Galileo also mentioned his first new science:

> And recently I also finished finding all the conclusions, with their demonstrations, related to the forces and resistances of woods of different lengths, thicknesses and shapes: how they are weaker in the middle than at their ends, and how they will support greater weight if this is distributed all along the wood rather than at just one point, and the shape this should have so that it is equally resistant. This science is imperative to build machines and every kind of engine, and yet no one has performed this study to date.[7]

The deductive system of Galileo's science of materials already had been worked out around late 1608/early 1609. The manuscript *On Motion* (Galilei ca. 1602–ca. 1637) contains one folio concerned with the demonstration of a theorem later published in the second Day of the *Discorsi*, the part of that work most relevant to the science of materials (Galilei ca. 1602–ca. 1637, 102v). Watermark evidence exposed by Jochen Büttner in the course of his analysis of the manuscript suggests that the folio stems from Galileo's Paduan period (Büttner 2009), which supports Galileo's statement in his letter to Antonio de Medici.

Galileo certainly worked on some of the theorems of his science of materials in 1633 as well, when he sent some folios of his manuscript to Mario Guiducci (1584–1646) for revision.[8] In conclusion, although the version of Galileo's first new science as it is known today is certainly the result of work that took place between 1592 and 1636, when the final manuscript was ready, it is certain that the most intensive work on the science of the strength of materials had been accomplished while Galileo was resident in the Venetian Republic, that is, between 1592 and 1610.[9]

The Key Question of the Machine Makers

With his cantilever model Galileo tried to identify the resistance to fracture of a given solid body, for instance a prism, of known dimensions and material, and how this resistance is affected when its dimensions are hypothetically increased or

[7]From Galileo to A. de Medici, February 11, 1609, in *EN*, X:228–230. For the translation of the entire letter, see pp. 223ff.

[8]Andrea Arrighetti (1592–1672), who received the folios from Guiducci in 1633, also proved the content of one theorem. Galileo gladly accepted his suggestions and introduced them in the final version of the *Discorsi*. For more details, see Andrea Arrighetti to Galileo, September 25, 1633, in *EN*, XV:279–281 and Galileo to Andrea Arrighetti, September 27, 1633, in *EN*, XV:283–284. For the translations of the entire letters, see pp. 270ff and 273.

[9]Bertoloni Meli reached a similar conclusion in Bertoloni Meli (2006, 91), albeit by a different route.

decreased, and when a given weight is suspended from one of the extremities of the body. Thus described it sounds like a highly theoretical field of research, perhaps one originating from a modern physics laboratory. But this is a very misleading impression. Galileo's reflections on the resistance of prisms or cylinders are connected intimately with the problems dealt with by engineers, architects, shipwrights and especially machine makers when using timbers and cylinders of wood to construct machines, ships, weight-bearing structures for buildings, scaffoldings and the like.

Discussions about the commissioning of an engineering device were often held around a functioning model of the apparatus in question. Once the construction of the device in real size had been agreed upon, the next problem to arise usually involved the thickness of the device's components in real size. It was commonly believed that when the dimensions of a component, for example a wooden cylinder, were changed proportionally, its resistance to fracture would remain exactly the same.[10]

However, any carpenter, thanks to the experience he had accumulated, observed that proportionally changing the dimensions of a solid body decreased its resistance to fracture. This gap between theory and praxis was often bridged by early modern engineers, who theorized that the main cause for construction failures was either a lack of experience by the mechanician in calculating the force produced by the compound machine, or other natural hindrances that arose due to the irregularities of real materials in comparison with ideal matter. Lorini, for example, indicated that the mechanicians need to be able to:

> [. . .] build the proposed machines, and to know not only how to proportionally assemble and rule them, but, with the clarity that one needs, also to know how to find the force with the compass, that is, the multiplication of their levers, so that then, when making the work in real size, one is not defrauded from that force of it, as often happens to those who only trust the ease shown by the small Models, without knowing its necessary grounds.[11]

Complaining that there is no perfect rule as to the materials of which machines consist, Lorini also added:

> But the mind of the Mechanician, who has to guide and order the executors of the work, largely consists in being able to foresee the difficulties which are caused by the diversities of the materials with which one has to operate: and the more he has to be prudent with that because it is impossible to give a certain rule for such accidental hindrances [. . .].[12]

---

[10]The same resistance is in truth obtained by increasing the dimensions over-proportionally. Such a conception of building was followed and divulged by the Italian architects of the sixteenth century and related to the Vitruvian conception of modular architecture. This issue is extensively analyzed in Valleriani (2009a, especially on pp. 186–190).

[11]"[. . .] fabricare le proposte machine, e quelle sapere proportionatamente non solo comporre, & ordinare, ma con quella chiarezza, che ancor si ricerca, saper co'l compasso ritrouare la forza, cioè la multiplicatione delle sue lieve, accioche poi nell'effettuar l'opera in forma reale, non si venga a restare ingannati di tal sua forza, come spesso accade a quelli, che confidano solo nella facilità, che mostrano i Modelli piccoli, senza sapere i necesiarij suoi fondamenti" (Lorini 1609, 196).

[12]"E però il giudicio del Mecanico, che deue ordinare, e comandare agli essecutori dell'opera, consiste in grandissima parte nel sapere preuedere le difficultà, che apportano le diuersità delle materie,

The passage from the model of a machine to a full-scale specimen, from the model of a building to the real building, from small to large, was ultimately the most urgent problem for craftsmen such as, for example, machine makers. Success in bridging this gap was what distinguished bad craftsmen from good ones, and amateurs from masters. Galileo's first new science was supposed to help the mechanicians in dealing with such problems.

Galileo's Cantilever Model

With the cantilever model, the second of the models developed by Galileo within the framework of his first new science, he tried to identify the resistance to fracture of a certain given prism of known dimensions and material, when the dimensions of the prisms were hypothetically increased or decreased and when one extremity was fixed, for example, driven into a wall, and a given weight suspended from the opposite extremity.

Galileo framed the cantilever model by considering timber driven into the wall as a lever, the principle of which Galileo expressed in these terms:

> [. . .] the force related to the resistance is the inverse ratio of the distances which separate the fulcrum from the force and resistance respectively. (*EN*, VIII:152)

Given a prism driven into the wall at one end and a weight suspended at the other (Fig. 4.1), in accordance with the principle of the lever and without taking into consideration the material constituting the prism, the lever would act in such a way that a given weight would cause a fracture at the base of the prism where it is driven into the wall, as governed by the following relationship between the resistance to fracture, the dimensions of the prism, and the suspended weight:

> [. . .] the magnitude [*momento*] of the force applied at C is related to the magnitude [*momento*] of the resistance, found in the thickness of the prism, i.e. in the attachment of the base BA to its contiguous parts, by the same ratio at which the length CB is related to half the length BA; [. . .]. (*EN*, VIII:156)

If one considers real prisms, that is, the materiality of the prism, half of the weight of the prism has to be added to the magnitude of the force applied in C, which is represented by weight E. This establishes a relationship between the dimensions of the prism, including its thickness and its weight. The resistance to fracture is represented by half of the thickness, and the cause of the fracture is the weight, either a suspended weight added to the prism's own weight, or the prism's own weight alone.

Galileo then sought to determine how both the resistance to fracture (i.e. the thickness of the prism) and its weight are related, by comparing two prisms of

---

con che si conuiene operare: e tanto più deue in ciò esser cauto quanto che di tali impedimenti accidentali non se ne può dar regola sicura; [. . .]" (Lorini 1609, 196).

Fig. 4.1 Illustration of Galileo's cantilever model (Galilei 1655, 86)

proportional dimensions but different sizes. Considering weight first, Galileo compared two prisms of the same material, with the same thickness and different lengths, reaching the conclusion that:

> [. . .] the moments [of gravity] of the forces of prisms and cylinders which have the same thickness but different lengths, bear to each other a ratio double of that between their lengths, that is, they are as the squares of their lengths. (*EN*, VIII:159)

In other terms, the ratios of the weights of the two prisms is given by the ratios of the squares of their lengths.

Next he looked at two prisms of the same length but of different thicknesses. Galileo stated that:

> In prisms and cylinders of equal length, but of unequal thicknesses, the resistance to fracture increases in the same ratio as the cube of the diameter of the thickness, i.e. of the base [. . .] [,] (*EN*, VIII:160)

which means that the prism's resistance to fracture is given by the third power of the diameter of the base.

Integrating the final two conclusions[13] offers a solution to the old mechanicians' problem of the proportions of machines. If an engineer wanted to retain the structure

[13]Galileo first established a relation between weight and resistance to fracture: "Prisms and cylinders which differ in both length and thickness offer resistances to fracture [i.e., can support at their ends loads] which are directly proportional to the cubes of the diameters of their bases and inversely proportional to their lengths" (*EN*, VIII:162–163).

of a mechanical device as it was in the form of a small model and transfer it to the bigger machine, and, more importantly, if that engineer wanted to maintain the same resistance to fracture presented by the small model, then he had to build the mechanical device with increased dimensions so that the thickness of the components was increased by a power of three over the original model. The fact that the weight of the given device, which is the cause of the fracture, increases by a power of two when its dimensions are increased proportionally, constitutes a size limit at which any object will collapse under its own weight.

The Origins of the Renaissance Engineers' Cantilever Model

Before Galileo had published his science of materials, mechanicians were not left to their own devices. As mentioned, engineers, architects, machine makers and shipwrights already had a body of theory. They believed that two machines, different in size but built of components linearly proportional to each other, would also have the same resistance to fracture. Reducing this to the example of the cantilever driven into a wall, they believed that two cantilevers of the same material, different in size but proportional to each other as regards their thickness, length and width, would have the same resistance to fracture as well. If this could not be observed, that is, if the larger cantilever or compound machine was weaker, this was believed to be due to either those unpredictable irregularities of the material or, in the case of compound machines, to the mechanician's lack of experience.

Engineers' opposition The French military architect Antoine de Ville (1596–1674), who also did some of the revision on the first two Days of the *Discorsi* before the work was published, was a vocal opponent of Galileo's theory. Antoine de Ville was a famous military architect, also employed by the Venetian Republic from 1632 to the beginning of 1635. During these years he was in close contact with Fulgenzio Micanzio, who had been the closest collaborator of Fra Paolo Sarpi and was in charge of correcting the proofs of the *Discorsi* and acting as an intermediary for their publication in the Netherlands in 1635.[14] Thanks to Micanzio's mediation, de Ville and Galileo entered into direct epistolary exchange.[15] De Ville, who had published a treatise on military fortification that had been widely circulated and even reprinted several times some years earlier in 1628, read the folios of the first two Days of the *Discorsi*. After several vigorous discussions with

---

[14] For biographical details about Fra Fulgenzio Micanzio, see Favaro and Galluzzi (1983, II:700–736).

[15] Galileo sent the first folios of his *Discorsi* to Fra Fulgenzio, who organized a reading group. Besides Micanzio and de Ville, the group was constituted of the Paduan mathematician Andrea Argoli (1570–1656), the Venetian engineer Francesco Tensini (1580–1630), Galieo's ex-pupils Paolo Aproino (1586–1638) and Alfonso Antonini (1584–1657), and the Venetian astronomer Marcantonio Celeste. For more biographical details about Antonio de Ville, as well as on the entire correspondence between him and Galileo, see also Vérin (2001).

Micanzio, he decided to write Galileo about his doubts, as he did in a letter of March 3, 1635:

> One says that, since a timber breaks due to its own weight, hence the matter destroys itself and the machine as well due to its gravity, which does not improve the force. One answers that for this there is a rule. But which one, and with which proportion, and with which matter? Since each material is different—the iron supports very heavy hanging weights, the wood carries them placed upright upon it—then which demonstration is able to show all of the imperfections that can be found in the materials, since *there is no science of the singulars*? These are all different, and for these differences or affectations, if we do not want to call them imperfections, one cannot give any convenient rule. And not only is there no rule for all of them, there is no single rule for those materials of the same species. [. . .] And while one does not want to call these things defects of the matter, in any case they make the art faulty, as these accidents cannot be recognized in small machines, but become evident in the large ones since they are increased in force and in weight. [. . .] You also observed that a siphon cannot attract for a height of more than 18 feet, no matter how thick and high it is [. . .]. One must say: this is not a defect of the machine, but of the water.[16]

De Ville was simply not able to accept that other general rules concerning matter could be valid in addition to the law of the lever. He very clearly reported his observations and his experience, according to which bodies similar in proportions but different in dimensions do not have the same resistance to breakage, and undoubtedly saw the cause of this behavior in the imperfections of the materials. Finally, De Ville also quoted a strong epistemological obstacle for the acceptance of Galileo's rules: the idea that a science of the singulars, as de Ville says, is impossible.

Engineers and architects like Lorini, Ceredi and de Ville did not create their theory on the strength of materials. They received it in its present form from the works of the Aristotelian commentators of the sixteenth and seventeenth centuries, who focused their speculations on Aristotle's *Mechanical Questions*, in particular on Question 16. Galileo himself pointed out this aspect in his *Discorsi*.

Aristotle's mechanics in Galileo's *Discorsi* Galileo's *Discorsi* are written in a dialogical form, as a conversation between the speakers Sagredo (the Venetian pragmatic thinker), Salviati (Galileo) and Simplicio (the Aristotelian thinker). Galileo first had Simplicio quote Aristotle's *Mechanical Questions*, needing to introduce the principle of the lever as fundamental knowledge in order to approach the cantilever model (*EN*, VIII:152).[17] The *Mechanical Questions* are then mentioned again between Proposition VI, according to which the moments composed of gravity and the dimensions of two prisms are compared with each other, and Proposition VII, which establishes the physical meaning of the previous statement:

> Among heavy prisms and cylinders of similar figure, there is one and only one which under the stress of its own weight lies just on the limit between breaking and not breaking: so that every larger one is unable to carry the load of its own weight and breaks; while every smaller one is able to withstand some additional force tending to break it. (*EN*, VIII:165)

[16]From A. de Ville to Galileo, March 3, 1635, in *EN*, XVI:221–228. Author's italics. For the translation of the entire letter, see pp. 277ff.

[17]Galileo admitted the temporal priority of Aristotle's formulation of this principle, but he also suggested using the one by Archimedes because he considered it more rigorous.

Given two solid bodies of a certain form and of a certain material, there is one set of dimensions and one set of proportions for the largest possible body. If one maintains the proportions of the smaller body and exceeds this set of dimensions, the body will inevitably fracture under its own weight.[18]

Galileo quoted Aristotle's *Mechanical Questions* in his reasoning because Aristotle's Question 16 approaches a case apparently similar to Galileo's cantilever model:

> Why do pieces of wood, the longer they are, become weaker and bend more while they are being lifted up, and this also when one, which is as short as two cubits, [is] thin, and the other, which is a hundred of cubits [long], is thick? Is it perhaps because the lever and weight and fulcrum are formed, while the length of the timber is being lifted up?[19]

Aristotle considered the process which leads to the bending and the fracture of a cantilever to be a mechanical one, which therefore can be explained by appealing to the law of the lever formulated at the beginning of his text. Therefore, the longer the timber is, the weaker it is. The fulcrum is where the hand is placed, and this is toward one extremity of the timber. As this text clearly shows, although Aristotle was comparing solids of the same matter and shape, only their length is taken into consideration in a quantified form and not all of their dimensions, as the key problem of the machine makers required. In the *Discorsi* Galileo suggested, therefore, that his cantilever model be compared with the one emerging from the Aristotelian tradition as it was passed down and transformed in two later commentary works: by Giovanni di Guevara in 1627 (Aristotle and Guevara 1627) and by Giuseppe Biancani (1566 ca.–1624) in 1615 (Aristotle and Biancani 1615),[20] authors with whom Galileo was personally acquainted, and who transformed Aristotle's cantilever model such that it could address the practical problem of developing a model into a full-scale machine.

---

[18]Galileo's specified that once the maximum thickness of a prism, given its length, is found, "each smaller [prism] [...] will be able to resist some additions of new violence, in addition to that of the own weight." (*EN*, VIII:166). Such a statement is evidently particularly concerned with the problems of machine makers. In fact, once the maximum length for the given thickness is known, it becomes possible to assemble components by decreasing their length such that the total weight cannot cause the device to collapse.

[19]Translation based on the Greek critical edition Aristotle and Bottecchia Dehò (1982). The translation is one of the results of the workshop *Q.XVI* held at the Max Planck Institute for the History of Science in Berlin on August 2007. For more details, see Valleriani (2009a, 197–198).

[20]Biancani is cited in a note on the copy of the manuscript of the *Discorsi* destined to become a failed publication in Prague. The manuscript was sent to Giovanni Pieroni, who was supposed to print the book far away from the Roman censors. The publication of the *Discorsi*, in fact, was first attempted through the mediation of Giovanni Pieroni, the emperor's military engineer. A friend of Galileo, he never succeeded in accomplishing this task because of the various professional obstacles placed in his path, which obliged him to travel frequently. Galileo had part of his manuscript copied—the whole first Day and part of the second—and then sent it to Pieroni, adding some further notes by hand. The note concerned with Biancani's work is published in *EN*, VIII:165, n 1. The copy of the manuscript of the *Discorsi* sent to Pieroni, which was then returned to Galileo after Pieroni's failure, is now at the Biblioteca Nazionale Centrale of Florence, Banco Rari, A. 5, p. 2, n. 13. For an introduction to this manuscript, see *EN*, vol. VIII, *Avvertimento* of A. Favaro, pp. 20 ff.

Giuseppe Biancani The Jesuit Giuseppe Biancani (1566–1624) first met Galileo in Padova at some point during Galileo's stay there.[21] He was involved in two debates concerned with Galileo's work. The first was about Galileo's solution to calculate the height of the lunar "protuberances,"[22] and the second about the priority of the discovery of sunspots in 1613.[23] Despite some ambiguities, especially on the occasion of the debate of 1613, Biancani always professed himself to be Galileo's friend. According to his publications, Biancani was a representative of the scientific view as promoted by the Peripatetics after the Counter-Reformation. However, as Ugo Baldini showed (Baldini 1992, 217–250) by analyzing the work of the censors of the Company of Jesus, Biancani always tried, unsuccessfully, to provide positive evidence for the "new Galilean science," especially as concerned the astronomic system and Galileo's work on floating bodies.[24] Biancani's two main works are the *Loca mathematica* of 1615, part of which is a commentary on Aristotle's *Mechanical Questions* and, in 1620, a work on the sphere, *Sphaera mundi* (Biancani 1620).

Giovanni di Guevara Not many details about Giovanni di Guevara are known. Descendant of a noble Spanish family that had emigrated to Sicily, he was born in Naples. Later, in his capacity as General of the Congregation of the Theatine Clerics Regular Minor, he became a close collaborator of Cardinal Barberini, with whom he also spent some time in France. Pope Urban VIII also sent him as *legatum a latere* to Spain to visit King Phillip IV. At the beginning of 1627 he was appointed Bishop of Teano, where he remained until 1636, when he returned to his native Naples. In 1626 Guevara and Galileo met in Florence and in Bellosguardo,[25] Galileo's first residence after returning from Padova to Tuscany. On this occasion they engaged in discussions concerning the problem known as "Aristotle's wheel," Question 24 in his *Mechanical Questions*.[26] In 1623 Guevara was appointed to evaluate whether it was "appropriate" to publish Galileo's *Il Saggiatore* and subsequently make his recommendation to Cardinal Barberini, who ultimately gave his *placet*.[27] In 1622 Giovanni di Guevara published two books, *Horologio spirituale di Prencipi* and *De*

---

[21]G. Biancani to C. Grienberger, June 14, 1611, in *EN*, XI:126–127. This letter was sent by Grienberger to Galileo who made a copy of it by hand.

[22]Galileo to C. Grienberger, September 1, 1611, in *EN*, XI:178–203 and the letter cited in the previous note.

[23]G. Biancani to G. A. Magini, May 17, 1613, in *EN*, XI:509.

[24]Biancani intended to publish in his *Loca mathematica* a chapter on the science of floating bodies—*Brevis tractatio de iis quae moventur in aqua unde caput ultimum de caelo explicabitur*— where he substantially supported Galileo's *Discorso intorno alle cose che stanno in su l'acqua*. However, the censor Camerota prohibited the publication of this chapter (Baldini 1992; Ceglia 1997). On the controversial relationship between Biancani and the Jesuit censors within the general framework of the prohibition to teach in a way contrary to Aristotelian physics from the beginning of the seventeenth century onward, see Blackwell (1991, 148–153).

[25]G. di Guevara to Galileo, July 17, 1627 in *EN*, XIII:368–369.

[26]G. di Guevara to Galileo, November 15, 1627, in *EN*, XIII:377–378. For the translation of the entire letter, see pp. 268ff.

[27]M. Guiducci to Galileo, April 18, 1625, in *EN*, XIII:265–266.

interiori sensu, sending Galileo a copy of them in 1626 as a token of his friendship.[28] In late 1627 Guevara released for publication his last work, a commentary on Aristotle's *Mechanical Questions*,[29] and urgently requested that Galileo summarize their discussion about Question 24 Galileo answered quickly, in January 1628,[30] providing some general considerations and promising to send more details. Although he never did so, Guevara went ahead with printing and in April 1629 sent Galileo two copies of his work, which fails to cite Galileo at all in its lengthy commentary on Question 24 (Aristotle and Guevara 1627, 205–224). Galileo cited and criticized Guevara's commentary in his *Discorsi*, however, though not as it concerns Question 24 but rather number 16, namely Aristotle's study on the behavior of the cantilever.

Biancani's cantilever model Giuseppe Biancani is quoted in the manuscript of the *Discorsi* in a note at the margin of Proposition VII. The note explicitly quotes Biancani's *Loca mathematica* and the page: "car. 177,"[31] where Question 16 is discussed. Biancani considered two timbers, one shorter than the other (Fig. 4.2). After having quoted Aristotle, according to whom the longer should bend more than the shorter, Biancani wrote that this happens:

> because in reference to the larger [timber], the further the weight of the same timber, which is in A, is away from the fulcrum B, the more it pushes downward, in comparison to the smaller timber.[32]

In accordance with the law of the lever and considering the weight of the timber as placed on the extremity opposite to the one where the fulcrum is, Biancani concluded correctly that, the longer the timber is, the more it should bend. This is correct and still in agreement with both Aristotle and Galileo. However, the question is whether the resistance to bend or to fracture remains the same by proportionally increasing the dimensions of the timber. In other words, the height and the depth

Fig. 4.2 Illustration of Aristotle's cantilever model in Giuseppe Biancani's commentary work of 1615 (Aristotle and Biancani 1615, 177)

[28] G. di Guevara to Galileo, November 21, 1626, in *EN*, XIII:341–342.

[29] G. di Guevara to Galileo, November 15, 1627, in *EN*, XIII:377–378. For the translation of the entire letter, see pp. 268ff. Guevara's commentary work is Aristotle and Guevara (1627).

[30] G. di Guevara to Galileo, January 24, 1628, in *EN*, XIII:389–390.

[31] Biancani's discussion about Question 16 starts at car. 176.

[32] "[...] quia in maiori onus ipsius ligni, quod circa A, deorsum premit lo[n]gius distat ab hypomoclio B, quàm in minori ligno" (Aristotle and Biancani 1615, 177).

of the timber had to be taken into account mathematically as well. Biancani, whose commentary is characterized by a certain brevity and schematism, could not avoid addressing this topic so relevant for all of the machine makers of his day:

> [. . .] I believe that, if between the length of the larger timber and its thickness there were the same proportion as between the length of the smaller timber and its thickness, so that it would be divided by the fulcrum with the same relation, they would then bend in the same way, since the weights would have the same relation to the distances to the fulcrum [. . .].[33]

In the same words as Biancani, Simplicio introduces the reasoning which leads to Proposition VII in Galileo's *Discorsi* (*EN*, VIII:164).

Di Guevara's cantilever model Guevara took into consideration two objects, a long lance or spear and a short branch of weaker matter (Fig. 4.3). Initially he neglected to compare the two objects as concerns the materials of which they are constituted, stating that the spear will bend more than the branch:

> [. . .] because the weight located in B is at a distance from the fulcrum C greater than that between E and the same [fulcrum] F; and since it weighs more, it bends downward, gradually starting from the straight line, on which it was when it stood or lay at the bottom.[34]

Guevara simply applied the law of the lever, thus obtaining the first result that the longer the timber is, the more it bends. But he introduced the relevant difference of considering two objects of different materials. In fact, Guevara had a very peculiar theoretical explanation in mind for the "bending." He considered the solid bodies to be constituted of particles and then tried to accommodate this view with the principle that "nature acts going through all degrees." Therefore, a lance can bend only gradually and this means that the particles constituting its lower part,

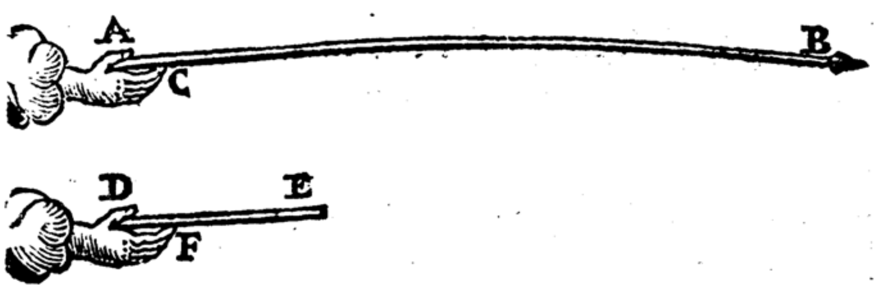

Fig. 4.3 Illustration of Aristotle's cantilever model in Giovanni di Guevara's commentary work of 1627 (Aristotle and Guevara 1627, 164)

---

[33] "[. . .] existimo, quod si maioris ligni longitudo ad eiusdem crassitiem haberet ea[n]dem proportionem, quàm minoris longitudo ad eiusdem crassitiem, sicq[ue] vtrumq[ue] esset ab hypomoclio in eadem ratione diuisum, fore, vt vtrunq[ue] eodem modo inflecteretur, quia haberent pondera eandem rationem ad distantias ab hypomoclio [. . .]" Aristotle and Biancani (1615, 177).

[34] "[. . .] pondus tamen constitutus in B magis distat à fulcimento C, quàm quod co[n]stituitur in E ab ipso F; magisq[ue] propterea grauitat, & inclinat deorsum, paulatim recedendo à rectitudine, quam stans, vel in solo iacens habebat" (Aristotle and Guevara 1627, 164).

the concave one, must be able to condense (*constipatio/condensatio*), whereas the particles constituting the upper part, the convex one, to rarefy (*laxatio/rarefactio*). Finally, according to the law of the lever, the longer timber bends more because of its weight; in particular, it bends more than a branch because, although the material constituting the branch is weaker than that of a spear, it is also lighter. But this means that a short but thick object, because its thickness makes it heavy, should also bend, which is obviously wrong. In order to cover this case, Guevara introduced the theory of the particles, according to which:

> If the shortness of the timber is compensated by a great thickness, that same thickness on the other hand, on account of the greater number of particles, some of which must condense and some others rarefy, will hinder when that bending takes place.[35]

Guevara's theory is complete. He first introduced a precarious example in which two objects constituted of different materials are taken into consideration. By explaining their behavior only according to the law of the lever, he ran the risk of reaching the incorrect conclusion that short but very thick objects should bend. To avoid this conclusion he introduced an almost "atomistic" view of the solid bodies, obtaining the important result that the thickness of the object could be determined as resistance against bending or fracture. In this sense also Guevara transformed the Aristotelian cantilever model in order to take into account in a quantified way the other dimensions of solid bodies, so to approach the key problem of the machine makers (Valleriani 2009a, 193–196).

The question of the machine makers, in fact, which involved two objects that were constituted of the same material, different in dimensions and similar in proportions, was pressing to Guevara as well. Conscious that his model could not determine the resistance of the timbers elevated parallel to the horizon, he introduced an external assumption: by maintaining the proportions, the resistance to bend or to fracture should remain the same. Contrary to Biancani, however, Guevara also watched craftsmen at their work, observing that:

> [. . .] one does not sufficiently see the correspondence that longer and shorter bend more or less equally easily.[36]

Given his assumption and the right observations, Guevara concluded his comment by searching for a possible explanation for this "observational gap." He added:

> Probably it can be said that one observes first that there are dispositions of the matter, so that in itself it is heavier or lighter, denser or more rarefied, stronger or weaker. Thus on these [dispositions] frequently it depends that some bodies acquire more facility toward the

[35]"[. . .] si brevitas ligni compensetur magna crasssitiei, obstabit ex alio capite ipsamet eadem crasssities propter maiorem multitudinem partium, quarum aliæ constipari, aliae autem laxari debent cum sit ipsa inflexio" (Aristotle and Guevara 1627, 165).

[36]"[. . .] æquè facilè inclinetur magnum, ac paruum, seu longum, ac breue, non satis videtur constare" (Aristotle and Guevara 1627, 165).

> inclination from the greater length than difficulty from the greater thickness. [And] others, indeed, behave in the opposite way.[37]

Guevara had a mixed theory which could have been applied similarly to his assumption that, by maintaining the proportions, two bodies different in dimensions show the same resistance to bend, and to its opposite. He chose the first assumption, and concluded, in order to explain contradictory observations, that there are so many characteristics of matter that its behavior cannot actually be determined. Accordingly:

> [. . .] the proportion, that makes easier or more difficult the bending with one sort of wood, does not have the same effect with another sort [of material] or with the same sort of wood, and lead iron or steel. The reason why nobody can determine anything without physical proof is thus due to the disposition of the matter and the different proportions, which, in various ways, lead to greater or smaller magnitudes of the bodies.[38]

Galileo recognized in the *Discorsi* that Guevara had accomplished an important step toward the comprehension of the cantilever model, and probably was referring to the fact that Guevara had been able to determine the two factors relevant for describing its behavior, namely longitudinal dimensions and thickness. However, Guevara proceeded by making an assumption that contradicted his observations, offering the indeterminateness of the nature of matter as an explanation for this gap.

In the *Discorsi*, Salviati, Galileo's spokeman, admitted to Simplicio that he had shared this conviction with Guevara and Biancani for a given time until, after certain and very different observations, he began to believe that it was a mistake. Therefore the young Galileo, Biancani and Guevara, and most of the architects and engineers all agreed in considering two objects of the same matter and with the same shape, and with different but proportional dimensions, to be equally resistant.[39] As will be shown, Galileo achieved his new theory thanks to the practical knowledge the shipwrights of the Venetian Arsenal shared with him, but it is on the basis of Aristotle's *Mechanical Questions* that Galileo was able to spend such a fruitful period at the Arsenal. Galileo went to the Arsenal primarily to research what were known as the Aristotelian Nautical Questions.

---

[37] "Probabiliter tamen dici potest, spectandum primò esse qualitatem, ac dispositionem materiæ, vt si grauior, aut leuior; densior, aut rarior; fortior, aut imbecillior in se sit. Nam frequenter ex ijs pendet, vt nonnulla corpora plus facilitatis ad se inclinandum acquirant ex maiori longitudine, quàm difficultatis ex maiori crassitie: Alia verò contra" (Aristotle and Guevara 1627, 165–166).

[38] "[. . .] proportio, quæ auget facilitatem, aut difficultatem inflexionis in vna specie ligni, non auget in alia sicut non æquè in ligno, ac ferro plumbo, aut calibe. Quare nihil determinari potest quo ad hoc nisi perspecta, vt diximus dispositione materiæ, variaq[ue] proportione, quæ diuersimodè iuxta maiorem, aut minorem corporum magnitudinem operatur" (Aristotle and Guevara 1627, 166).

[39] Many professionals considered this conception to be an original Aristotelian one, although the original argument of Question 16 considers only the dimension of the length of the solid body. This is the consequence of the use made by early modern commentators of ancient scientific texts as a basic theoretical structure for the generation of new knowledge during the Renaissance (Valleriani 2009a).

Galileo at the Arsenal: The Aristotelian Nautical Questions

When Galileo began visiting the Arsenal, he probably did it with the precise aim of using his visits to further investigate a certain group of Aristotelian Questions concerning shipbuilding and navigation. These are the Questions 4,[40] 5, 6, and 7.[41]

The textual evidence of Galileo's research at the Arsenal on the basis of Aristotle's Nautical Questions consists of mere fragments, later collected by Galileo's pupil Vincenzo Viviani and published by Favaro in the *Edizione Nazionale* (*EN*, VIII:609–610). Unfortunately, it is unclear exactly when Galileo wrote these fragments, and no watermark analysis is yet available.[42] These fragments are grouped under the title *Nell'arte navigatoria* (*On the Art of Navigation*). They primarily concern the functioning of several components of ships.

Question 5 Aristotle's Question 5 on the functioning of the rudder is the following:

> 5. Why does the rudder, which is small and at the end of the vessel, have such great power that it is able to move the huge mass of the ship, though it is moved by a smaller tiller and by the strength of but one man, and then without violent exertion? Is it because the rudder is a bar, and the helmsman works a lever? (Aristotle and Hett 1980, 355)

[40]Question 4 will be discussed last.

[41]Galileo's manuscript *Delle macchine*, which was introduced in the previous chapter, begins with an introduction that traces the *Mechanical Questions* in such a way to dispel any doubts about Galileo's familiarity with the Aristotelian text since 1593. In 1598, moreover, Galileo held a public course on that text (*EN*, XIX:120). The first reference to this text in one of his printed publications dates back to 1612, in the *Discorso intorno alle cose che stanno in su l'acqua* (*EN*, IV:57–140). Furthermore, throughout Galileo's correspondence it is evident that Galileo's confrontation with Aristotelian mechanics certainly continued until at least 1638, when he informed Elia Diodati, the Medici Ambassador in Paris, that he would like to write a book of *Problemi spezzati* (*Broken Problems*) in the wake of Aristotle's *Mechanical Questions* and *De incessu animalium*. For more details, see Galileo to Elia Diodati, January 23, 1638, in *EN*, XVII:262. Galileo's unpublished treatise constituted of "interrupted problems" was in fact begun, but remained incomplete. It consists of twelve problems voiced in the form of indirect questions. Their answers were written by Galileo's son, Vincenzo Galilei, partly under his father's guidance. Galileo and Vincenzo Galilei's treatise of *Problemi spezzati* is published in *EN*, VIII:598–607. Galileo's intention to write such a treatise is also revealed in the following letters: Galileo to M. Bernegger, July 15, 1636, in *EN*, XVI:450–452, especially p. 452, where Galileo called them *Problemi naturali e matematici*, Galileo to E. Diodati, November 7, 1637, in *EN*, XVII:213, where they are called *Problemi spezzati, fisici e matematici*, Galileo to G. B. Baliani, January 7, 1639, in *EN*, XVIII:10–13, especially p. 13, where they are called *Problemi e questioni spezzate*.

[42]Galileo's fragments related to nautical issues represent a small group of fragments among all of those collected by Viviani. In general, most of the fragments take the form of questions about either observations made by Galileo himself or topics suggested by other authors. The topics of the fragments are quite diverse, and most of them seem to be memoranda for further research or problems whose solutions Galileo included or wanted to include in his writings.

Galileo's fragment on the same topic reminded him of research to be accomplished to answer the following question:

> Which is the use of the rudder and how, with it, one turns the vessel with so much ease. (*EN*, VIII:609)

Galileo's question evidently follows along with that of Aristotle, showing that he effectively made use of Aristotle's text. Unfortunately it is not possible to compare the answers the two authors gave for this question because Galileo never published a single word on the topic, although he did write a whole *Discorso sul timone* (*Dialog on the rudder*) which is now lost. Today we have no choice but to believe the words of Galileo's friend Giovanni Ciampoli (1589–1643), who read the text in Rome in 1625, declaring it to be a "very noble dialog."[43]

A letter written by Niccolò Aggiunti (1600–1635) in 1634 offers further testimony that Galileo was considered as an expert on the functioning of the rudder.[44] His former pupils Niccolò and Ludovico Aggiunti proposed to him the following problem:

> How can one make a boat go from one side of a river with a very rapid current to the other without moving anything but the rudder of said boat?[45]

For the problem (Fig. 4.4, left), which was presented by Ludovico, Niccolò suggested that the only solution would be to pass a rope through a ring placed at the

Fig. 4.4 *Left*: Illustration of the problem formulated by Niccolò Aggiunti and sent to Galileo in 1634 (*EN*, XVI:50). *Right*: Illustration of the same problem, but formulated by Bernardino Baldi and published posthumously in 1621 (Baldi 1621, 48)

[43]For evidence that Galileo wrote a dialog on the rudder and that Ciampoli possessed it, see G. Ciampoli to Galileo, February 15, 1625, in *EN*, XIII:254 and G. Ciampoli to Galileo, December 28, 1625(4), in *EN*, XIII:295.

[44]N. Aggiunti to Galileo, February 22, 1634, in *EN*, XVI:49–50. For the translation of the entire letter, see pp. 274ff.

[45]From N. Aggiunti to Galileo, February 22, 1634, in *EN*, XVI:49–50. For the translation of the entire letter, see pp. 274ff.

boat's bow, and fix that rope on the two banks of the river. Unfortunately Galileo never responded to this problem because of the many obligations he had to fulfill due to his troubles with Roman censors during this period, but even this scant evidence clearly shows that Galileo took this topic under consideration seriously enough to dedicate a *Discorso* to it, and thus also to make himself known as an expert concerning the functioning of the rudder. The problem suggested to Galileo by the Aggiunti brothers is also interesting because it appears in the same formulation in the commentary on Aristotle's *Mechanical Questions* that was written by Bernardino Baldi (1553–1617) and published posthumously in 1621 (Fig. 4.4, right).[46]

Question 6 Aristotle's Question 6 is the following:

> 6. Why is it that the higher the yard arm, the faster the ship travels with the same sail and the same wind? Is it because the mast acts as a lever with its base in which it is fixed as a fulcrum? (Aristotle and Hett 1980, 361)

Aristotle considered the system constituted of vessel, mast and sail placed at its top to be a lever. As the bottom of the mast was conceived as the fulcrum in this system, a higher sail meant that the force of the wind was applied further away from the fulcrum, such that the same wind produced more movement of the vessel on the sea. Following Aristotle, Galileo first asked himself:

> Whether it is true what Aristotle says, that is, that the higher the sail, the stronger it pushes the vessel; and whether this happens because of the reason adduced by him, and taken from the lever [,] (*EN*, VIII:609)

and then formulated the problem in a more specific way:

> Which is the use of the very small sail placed over the box [along the mast] of the ship. (*EN*, VIII:613)

Finally Galileo found the solutions to both his questions:

> Sail, though small, placed very high, helps to sustain the ship when it goes inclined [,] (*EN*, VIII:611)

and:

> How childishly wrong is Aristotle when he assigns the reason why the sail placed higher pushes the vessel more. (*EN*, VIII:611)

Galileo first investigated (by observing practical experts in shipbuilding, like the mastmakers and shipwrights of the Arsenal, and by posing questions on navigation to figures such as Venetian admirals and coxswains) the use of the upper sail, discovering that its role is decisive when the ship has to navigate "against" the wind, when a particular use of rudder and sails causes the ship to continue moving at an inclined angle. Finally it becomes clear that what Aristotle said, in the words of

---

[46]There is no evidence as to whether Galileo was familiar with this and other works of B. Baldi. The fact that N. Aggiunti did not quote the origins of the problem sent to Galileo seems to suggest that this question was circulating without any specific paternity. For an extensive analysis of Baldi's commentary on Aristotle's *Mechanical Questions*, see Becchi (2004).

Giovanni Battista Benedetti, another early commentator of Aristotle, "*verum non est*," (Benedetti 1585, 155) because:

> [. . .] the higher the sail that is struck by the force of the wind, the more the ship's prow is submerged in the water[47]

and therefore, the more the wind blows, the slower the vessel would move.

Although the analysis concerning Question 6 is also supported by a few documents only, it does show that Galileo must have been in contact with professionals of the art in order to understand the use of the upper sail. Its use for a peculiar navigatory method, however, was known by Aristotle as well and therefore by the readers of his work.

Question 7 Aristotle's seventh question, in fact, asks:

> 7. Why is it that, when the wind is unfavorable and they wish to run before it, they reef the sail in the direction of the helmsman, and slacken the part of the sheet toward the bows? Is it because the rudder cannot act against the wind when it is stormy, but can when the wind is slight and so they shorten sail? (Aristotle and Hett 1980, 361)

The art of navigation had certainly changed over the centuries, and this especially because ships were built differently. For example, in Aristotle's day the famous Greek *trireme* had an external rudder on one side,[48] whereas the Venetian galleys of the sixteenth century had the rudder placed at the back of the ship and in the middle. Galileo therefore, interested in the special method of sailing the Venetians called *a orza* (windward), felt the need to reformulate the questions in a more articulate way. Four other fragments, which Galileo presumably tried to forward to the masters of the Venetian Arsenal, each address detailed questions. The questions, on the topic of *Del navigare a orza* (*Navigating hauling to the windward*), are the following:

> How can one navigate with the same wind in different directions. (*EN*, VIII:609)
>
> If it is possible to move against the wind, or at least to keep oneself in one place without being pushed back, and how. (*EN*, VIII:609)
>
> How by navigating to the windward one can hold the ship straight toward the place where one wishes to arrive (*EN*, VIII:609).
>
> With which artifice one navigates almost diametrically against the wind, moving by staying on the sides[49] (*EN*, VIII:611).

Galileo's research about the motion of the ship focused on its propulsion: he started with the rudder, and then considered the wind as a propulsive force, taking

[47] "[. . .] quanto altius est velum, vi venti impulsum, tanto magis proram ipsius navis in aquam demergit" (Benedetti 1585, 155). Unfortunately, in this case, too, no other comments by Galileo can support this analysis. However, because of the obviousness of Aristotle's mistake, and since all of the early modern commentators on this question accord with this critique, it is supposed that what Galileo called the "childish mistake" corresponds to what was universally accepted at his time and expressed by Benedetti.

[48] For more details on ancient shipbuilding, see Sherwood (1997). For an analysis of early modern commentaries on Aristotle's Question 7, see Rank (1984, 41–46).

[49] Navigation *a orza*, because of the inclination of the ship, obliged a great part of the crew to be stationed on the opposite side in order to counterbalance the hull on the sea.

this model as a point of departure to investigate methods of sailing. Finally, to complete the context, he considered the oars. In this case, too, Galileo first followed Aristotle.

Question 4 Aristotle's fourth question deals with the functioning of the oar as propulsive device of ships:

> 4. Why do the rowers in the middle of the ship contribute most to its movement? Is it because the oar acts like a bar? For the thole-pin is the fulcrum (for it is fixed), and the sea is the weight, which the oar presses; the sailor is the force which moves the bar. In proportion as the moving force is further away from the fulcrum, so it always moves the weight more; for the circle described from the centre is greater, and the thole-pin, which is the fulcrum, is the centre. The largest part of the oar is within in the centre of the ship. For the ship is broadest at this point, so that it is possible for the greater part of the oar to be within the sides of the ship on either side. Therefore the movement of the ship is caused, because the end of the oar which is within the ship travels forward when the oar is supported against the sea, and the ship being fastened to the thole-pin travels forward in the same direction as the end of the oar. The ship must be thrust forward most at the point at which the oar displaces most sea, where the distance between the handle and the thole-pin is greatest. This is the reason why those in the middle of the ship contribute most to the movement of the ship; for that part of the oar which stretches inside from the thole-pin is greatest in the middle of the ship (Aristotle and Hett 1980, 355).

Aristotle considered the oar as a first-degree lever. The sea is the weight, whereas the fulcrum is the thole pin, on which the oar rotates. Because of the form of the ship, which is broader in its middle, Aristotle concluded that the internal part of the oar placed in the middle of the ship was longer than that of the oars toward stern and bow. Thus, according to the law of the lever, the oars in the middle of the ship should cause a greater effect as regards the propulsive force. However, although this explanation seems quite acceptable at first glance, it conceals some important difficulties.

A great debate arose around this topic during the second half of the sixteenth century, which clearly showed Aristotle's mistake. The solution was first provided by the famous Portuguese cartographer Pedro Nuñes, who published it initially in Basel in 1566 and then in Coimbra in 1573. When Galileo arrived in Padova, however, he was not familiar with Nuñes books. Thus he began, armed with his copy of the *Mechanical Questions*, by writing notes for future investigations.[50] Galileo wrote:

> And if it is true that those who row in the middle of the galley, row more than the others at stern or at bow, also for the reason of the lever (*EN*, VIII:609).

> Why are the benches of the galleys placed at oblique angles (*EN*, VIII:613).

> On the operations of the oars, and how not all of the force of the oarsmen is employed in pulling the oar, while the ship moves (*EN*, VIII:613).

---

[50]Nuñes work was known by Galileo in 1615 at the latest, when Giuseppe Biancani published his commentary on Aristotle's *Mechanical Questions*, reporting on Nuñes' solution to Question 4 in its entirety. For more details about the reception of this work by Nuñes, see the introduction to the reprint of Nuñes' work written and edited by Henrique de Sousa Leitão (Leitão 2000).

> The force which moves is employed completely only when it is applied to a mobile at rest; but when it [the mobile] has already received the motion, then only the excess of the moving virtue is that which works. Because of this it happens that while a coach is at rest, the horses need greater effort to move it than they do to preserve its motion (*EN*, VIII:613).

The first fragment cites Aristotle directly and amounts to an exact translation of the Stagirite scholar's question. The second shows that Galileo was already observing the rowing units[51] of the galleys, which effectively were constituted of oblique benches. The third coincides with the main point of Nuñes' argument to show Aristotle's mistake. As Nuñes and Galileo clearly stated, an oar is not a simple lever, as Aristotle considered it, but a lever which moves together with the ship. The fourth, finally, shows what became a typical distinction made by many Aristotelian commentators during the Renaissance, that is, the distinction between employing the force when the ship is at rest and when the ship is already in motion.[52]

Ship in motion and at rest The distinction between the last two cases was also typically related to a discussion concerning a natural phenomenon that apparently occurred often on wooden vessels: the formation of barriers consisting of a peculiar type of shellfish, in such a way that the motion of the ship was hindered. This shellfish was always designated by the same word in both Latin and Italian, namely *remora*.[53] Galileo was eventually considered as an expert not only on ship motion and stability, but also on shellfish and their effects on the motion of ships. In 1621, Galileo's friend Giulio Cesare Lagalla (1571–1624), professor of philosophy at the first chair of the *Collegio romano* in Rome, wrote Galileo the following:

> I am writing some pamphlets on philosophy and among them *De simpatia et antipathia*. And I need to think about the remora that hinders the ship in its movements. I try to reduce the cause of this effect, not to an occult cause, but to the obstacle that it could present to the ship, since the ship is in equilibrium within a liquid element where the smallest hindrance can cause the greatest effect, as we can see in the steelyard how each small difference of weight along the line lifts up a great quantity and greatly varies the motion in the center. And this can easily happen with the remora, in part because of the slowness of its fluid, by means of which it adheres so strongly to the keel or to the rudder of the ships, since it is a kind of conch or sea-snail, as Plinius says, half a foot in size, and because it has the fins of the conch projected outside and scattered in such a way that it seems to have feet, as Aristotle says, one can assume that it can cause hindrance to the motion of the ships in the water, the more because Plinius accredits the same effect to every kind of conch. Therefore, before I write this thought of mine, I wanted to kindly ask you for your opinion. So please

[51] A rowing unit of a Venetian galley was constituted of bench, oar, thole pin (and therefore protection). A large galley had from thirty-two to forty-six rowing units.

[52] The distinction between moving what is already in motion and moving what is stationary is also the main subject of Aristotle's Question 31 (Aristotle and Hett 1980, 405–406).

[53] The *remora* is a shellfish considered to have special influence on both the motion of ships and on pregnant women. Among the many ancient sources that mention this shellfish, the most relevant are Aristotle, *De Hist. Anim.*, Lib. 2, Ca. 14 and Plinius, *De Hist. Nat.*, Lib. 9, Cap. 25 and Lib. 32, Cap. 1. In modern Italian the word is still in use: a person who has *remora* is one who is indecisive or hesitant, like a ship which is being rowed but does not move.

> do me the favor of considering it and see whether one can determine it with mathematical reasons. If Your Lordship approves it, I will write it based on your authority.[54]

Unfortunately no answer from Galileo has survived, although there is good circumstantial evidence indicating that such an answer did exist.[55] Lagalla's letter testifies that Galileo was also considered an expert on the way a ship moved, how the oars worked, and on the stability of vessels.

Did the Venetian Arsenal Employ Galileo?

Galileo went to the Arsenal to address questions to shipbuilders. At least some of these questions were derived directly from the *Mechanical Questions* of Aristotle, as if they were a sort of schematic plot to guide his observation of the work of the *Proti*, the shipwrights of the Arsenal. This sort of Aristotelian apprenticeship at the Arsenal eventually made him a scientific authority among the members of this institution's executive body. During the first years of Galileo's stay in Padova, moreover, he befriended Giacomo Contarini, the Commissioner of the Arsenal.[56] Through the mediation of Pinelli, finally, Galileo was asked by Contarini to assist in resolving a specific problem concerning the rowing units of the galleys.

Galileo's involvement in the Arsenal Contarini's question was probably stated in the following terms: does it cause a difference in reference to the propulsive force performed, whether the support of the oars, which is assembled together with the side protections of the ship, is located inside or outside the live part of the vessel? Above deck a Venetian galley constituted of a live part and a dead part. The live

---

[54] From G. C. Lagalla to Galileo, July 30, 1621, in *EN*, XIII:72–73. Author's italics. For the translation of the entire letter, see p. 263.

[55] Although no evidence directly shows that Galileo's answer really existed, there are several indications suggesting that it did: first, because the correspondence between Galileo and Lagalla is quite copious; second, because the books by Lagalla that Galileo possessed and which are now preserved among the Galilean inheritance at the Biblioteca Nazionale Centrale of Florence are richly annoted in their margins, testifying that Galileo occupied himself with them; third, because Lagalla was, through his deep scholasticism, very closely acquainted with many members of the *Accademia dei Lincei*, as was Galileo; and fourth, because Galileo himself intended to support Lagalla for the chair of philosophy of the University of Pisa after Papazzoni's death (1614). Although Lagalla held such an important position as the first chair for philosophy at the *Collegio romano* for thirty years, and although it seems that as a physician he had an almost revolutionary approach to surgery, only two biographical papers on him can be found (Gallo 1986 and 1987). Many commissioned researches at the Barberini Collection in the Vatican Library and on the collection of his main pupil, Leone Allacci (1586–1669), at the Biblioteca Vallicelliana in Rome, failed to uncover such an *opuscolum* in response to Lagalla's request for an opinion, which presumably contains Galileo's view of the functioning of the oars and a discussion about the analogy of the movements of the ship to a steelyard.

[56] Galileo and Giacomo Contarini first met thanks to the cultural circle around the patron G. Vincenzo Pinelli, resident in Padova, who helped Galileo obtain his chair in Padova. Contarini may have been aware of Galileo's geometrical talent since 1589, when it was first attempted to obtain that chair for Galileo. For more details, see B. Zorzi to B. Valori, December 2, 1589, in *EN*, X:42.

part was located on the hull of the ship, while the dead one was the above-deck enlargement obtained by the construction of wings, or superstructures, on the sides of the ship. The protections were those handrails surrounding the above-deck area, within which the thole pins were assembled. Contarini, facing the technical possibility of enlarging the above-deck area of the galleys, and presumably inspired by Aristotle's fourth question, was probably asking himself and Galileo whether increasing the distance between the middle of the ship and the thole pins (the supports), would have changed those relations governing the propulsion power of the galley (the force-resistance ratios).

The emergence of Galileo's cantilever model Thanks to Galileo's written answer, the problem can be regarded in technical detail. On March 22, 1593, Galileo wrote to Contarini:

> Concerning the need to apply more or less force in propelling the vessel forward, it does not make any difference if the oar lies on the live or dead part of the deck, since all other circumstances are the same. And the reason is that, since the oar is practically a lever, as long as force, support and resistance divide it with the same proportion, it will operate with the same vigor, and this is a universal and invariable proposition. And I do not believe that making the wings in the galley will achieve anything but the ease of having more space for the soldiers and convicts, who otherwise could not be seated in rows of four or five per oar, especially toward stern and bow, if there were no wings. But if they could sit and row both in one way and in the other way, I do not necessarily believe that placing the protection inside or outside the live part of the galley would make any difference if, however, the oar is divided with the same proportion. And I do not see anything that could hinder or facilitate the rowing other than placing the protection further away from or closer to the handle: the closer it is, the more one can apply force. And the reason is the following, a reason that has perhaps not been investigated by anyone else: The oar is not a simple lever like any other one, indeed, there is a great difference for the following reason. Ordinarily the lever should have a mobile force and a mobile resistance and a support at rest, but in a galley support, force and resistance move. It follows from this that *support and resistance are the same* because when the blade of the oar is placed in the water, the water becomes the support, and the protection becomes resistance. But when the oar moves the water, in this case it becomes the resistance, and the protection is the support. And since, when the support is fixed, the whole force is applied to move the resistance, if the oar is immersed so that the water becomes almost immovable, then most of the force is employed to propel the vessel. On the contrary, if the oar is immersed so that the water is moved easily by the blade, then one is not able to apply the force to move the boat. And since the greater the length of the part of the lever is toward the force, the more easily one can move the resistance, when the part of the handle is very long, the water will be moved more easily, and hence its support will be weaker and one will propel the vessel less. On the contrary, when the same part between the protection and the force is shorter, then it will be more difficult to move the water with the blade and consequently, since it is needed as support, it is more solid and one is able to propel the vessel with more force. And one concludes that, the closer the protections are to the handle, the stronger the force can be applied in propelling the vessel, as the water is not able to be moved so easily with a blade very distant from the protection by a force close to the same protection. Hence, in such a case, the water functions more as support than resistance. All of this is very evident from experience.[57]

[57]From Galileo to G. Contarini, March 22, 1593, in *EN*, X:55–57. Author's italics. For the translation of the entire letter, see pp. 214ff. This letter was evaluated for the first time in Renn and Valleriani (2001).

For both Galileo and for Aristotle the oar is a lever, but whereas it is a first-degree lever for Aristotle, Galileo considers the oar *almost* as a lever. In particular, if the blade of the oar sinks deeply into the water, then the water can be considered to be the fulcrum of the lever, because, when the weight of the water displaced by the blade is very heavy, the ship, by means of its connections to the thole pins, is moved more efficiently than the water displaced. On the contrary, if the blade of the oar does not sink deep into the water or if the handle is long, then the weight of the water displaced is not heavy enough to function as a fulcrum and therefore it becomes resistance, while the thole pin is the fulcrum, as Aristotle said. The great difference, however, is that, according to Galileo, when the thole pins are the fulcra, mostly the water should move and not the ship, whereas, according to Aristotle, the same view with the thole pins as fulcra should explain the movement of the ship and not of the water.

In closing Galileo remarked, first, that the placement of the thole pins in relation to the longitudinal center of the ship does not change the propulsion power of the galley; and second, that the deeper the blade lies in the water, i.e., the closer the oarsmen are to the protection, the more the propulsive force of the oarsmen is transformed into the motion of the ship. Galileo did not yet see the possibility that the oars could also be longer and arranged on the ship in a way that it remains possible to have blades that sink deep into the water, but his theoretical approach was different than Aristotle's, shifting toward a model according to which the fulcrum of the lever is at the extremity opposite to where the force is applied. This is the theoretical framework within which he later developed his cantilever model, after having learned some qualitative data about the robustness of the oars from the professionals at the Arsenal.

Galileo's Apprenticeship as a *Proto*

From the perspective of the master of shipwrights, Galileo was neither right nor wrong. He was simply too abstract and ignorant of further real and relevant aspects. The letter with which Contarini replied to Galileo's answer introduced him to those aspects, launching what is called here his apprenticeship as a shipwright (*Proto*).

Practical knowledge's criticism Encouraged by Galileo to open his mind to "such mechanical problems," Contarini opened his answer with the statement that, "the oars which are being used are not proportioned to the body of the vessel,"[58] and, in his opinion, if the right proportion between them—oars and the body of the ship—were found, the problems related to the agility and velocity of the vessel would be solved. In a way apparently unrelated to this statement, Contarini continued by considering human force and its application. The better way for the oarsman to apply force is to push and pull the oar by keeping the handle in front of the

[58] G. Contarini to Galileo, March 28, 1593, in *EN*, X:57–60. For the translation of the entire letter, see pp. 216ff.

breast, and by moving while holding a position parallel to the horizon. To satisfy this condition and, obviously, to be able to operate the oar in the most efficient way, which means dipping it as deeply as possible into the water, the oar must therefore be very long. But the longer the oar, the heavier it is, that is, the longer the handle must be because of the increased number of oarsmen needed on the vessel to operate the heavy oar. But the length of the handle of the oar, Contarini continued, is given by a certain ratio to the width midships above deck; and the entire length of the oar is deduced by means of a ratio to the handle.[59] Thus, keeping in mind that a certain space is needed on a ship for benches, and for a gangway between them to position or move goods, artillery and soldiers, as well as space for soldiers toward the protection behind the last oarsmen, Contarini first pointed out to Galileo that the superstructures were imperative and then, above all, reminded him that long-handled oars are particularly important "because the handle not only moves the pole of the oar, which is outside the protection, but also acts as a counterweight for the mentioned oar." And calculating the force performed by the single oarsmen,[60] Contarini reached two conclusions:

> Therefore what one says cannot happen, that the longer the handle, the easier it is to move the water. And therefore its support will be weaker and the vessel will be propelled less [. . .].
>
> [. . .] it is certain that with a short handle, one will never have force both to steer the oar and to row it.[61]

Contarini concluded by summarizing and reordering his fairly scattered list of thoughts: (1) the oar must be long; (2) the oarsmen rowing toward the middle of the ship perform two kinds of movements, upward in pushing the blade as much as possible under the water level, i.e. closer to the ship, and forward; (3) the oarsmen closer to the protection, since they perform only one movement, that is, forward, apply most of the propulsive force; (4) the superstructures are relevant not only because they allow long oars to be fitted, but especially because the long handles allow more oarsmen per bench.

Contarini's reply seems to be a list of interrupted points, not always connected with each other and, what is more, relevant to Galileo's letter only in part. In its opening Contarini wished to find the right proportion between the oars and the body of the galley in order to improve the agility and the speed of the vessel. However, he concluded by stating only that a longer handle would improve the propulsive force

---

[59] The "practical knowledge" of the shipwrights of the Venetian Arsenal was codified in part in the form of sets of ratios, one for each ship model. Given some main measures and the model of the ship, the ratios provided a method to obtain the measures of all other components of a ship. As concerns the handle of the oars, its length had to be the half of the width of the ship midships above deck.

[60] The way Contarini suggests calculating the force applied by each oarsman at a single oar is based on a comparison between the virtual circles drawn by the blade and those drawn by the points of the handle where each oarsman works.

[61] From G. Contarini to Galileo, March 28, 1593, in *EN*, X:57–60. For the translation of the entire letter, see pp. 216ff.

of the rowing unit. In this sense Contarini addressed Galileo's conclusion according to which the longer the oar is, the more easily the water is moved and therefore the less propulsive force is exerted. Contarini also reminded Galileo that a large Venetian galley is such a big machine that not even all of the oarsmen along the same oar could be considered to work in the same way. He said that if the oar is very long, and if one considers only the work of the oarsmen positioned at its extremity in the middle of the ship, they would not be able to operate the oar lever or move the water so easily, because they are busy with not only one movement but two, forward and upward. Thus Galileo was right in principle, but only if the movement were abstracted to the extreme such that all of the force performed by the different oarsmen is considered to be a unique force applied only at the extremity of the oar lever. But an oar with a short handle is neither steerable nor rowable in practice.

The official inquiry Galileo's letter and Contarini's response seem to be a nearly isolated case, especially if only Galileo's published works are considered. A situation where an early modern manager quite versed in practical activities like Giacomo Contarini, then Commissioner of the Venetian Arsenal, "disturbs" the then professor for mathematics at Padova through Pinelli's mediation, merely to request of him a written opinion on a personal issue concerning the placement of the ships' protection seems quite unlikely, however. In fact, this exchange of opinions about the placement of the oars above deck was not an isolated or causal event, but emerged from the context of an official inquiry led by one of the ruling bodies of the Venetian Arsenal.

On February 9, 1592, the *Collegio della Milizia da Mar*—Committee for the Navy—promoted an official inquiry, which ended over one year later in June 1593. The inquiry was iniated by the *Savij* ("the sages") in order to find solutions for a spectrum of problems ranging from ship design and shipbuilding issues, to related expenditures, and architectural changes to the Arsenal itself, which were related to the former issues. Anyone considered relevant to this inquiry had to answer under oath by submitting a written document, personally signed. Giacomo Contarini, who, as Commissioner of the Arsenal, was in charge of the organization of the inquiry, kept a copy of many, probably all written documents produced as a consequence of this inquiry.[62] Both Galileo's letter and Contarini's reply are still kept in this register of documents.

The points of the inquiry Contarini related the order of the Committee of the Navy in full and the points to which the selected persons had to respond. The points are:

> [1.] in which way one can remedy the lack that the large galleys have in reference to the rowing unit, so that, on occasion, they can be rowed without being pulled.
>
> [1.1.] whether one has to enlarge the superstructures of those galleys.
>
> [1.2.] which quality of oars and of which length will be necessary to use.

[62]The documents produced during the inquiry and collected by G. Contarini are preserved in a bundle entitled *Fabrica di galee* (Contarini 1592–1593).

[1.2.1.] whether one has to provide those galleys with two oars per bench, or with one.

[1.3.] The expenditure which could be caused by this change.

[2.] The way to bring outside those galleys from the Arsenal, in which the superstructures were to be enlarged.

[3.] Beside this, speaking about everything which could seem to anyone to be of public relevance.[63]

Large galleys The inquiry concerned large Venetian galleys. This kind of ship had been built for the first time at the end of the fifteenth century, but only occasionally; its construction became systematic during the second half of the sixteenth century. The typical Venetian ship built in the Arsenal before and after the advent of the large galley was the "thin galley." This was a ship normally employed for military purposes, whereas the large galley was normally built for trade. However, the increasing power of enemy fleets, especially of the Ottoman one, and the fast development of fire artillery, obliged the Venetians to equip their ships with more and more powerful artillery. More powerful, larger and heavier artillery also required a more capable, resistant and larger ship, namely one large enough to host more oarsmen than were used in thin galleys, so that it was possible to push the vessel forward with greater speed. In the face of this challenge, the Venetians began using the large galleys for military purposes as well.[64] During the famous battle of Lepanto in 1571, for example, the large galleys turned out to be the ace up the Venetians' sleeve. Deployed transversely against the huge Ottoman fleet, they discharged their fire power while the fast thin galleys attacked the single ships from the sides.

Propulsion of large galleys There was a problem with large galleys. They were not able to move by means of their own propulsion and therefore, in the absence of wind, their own rowing normally needed to be complemented by towing by one or more thin galleys. Although on the occasion of the battle of Lepanto the slowness caused by this propulsion method had no negative effects on the success of the battle, from the protocols of the inquiry it is clear that:

[. . .] one can say that, on another occasion, they [the large galleys] could rather hinder than help [. . .] since they cannot follow a thin navy without being towed, they could be a cause of slowness and [for this reason] endless good occasions could be missed. and anyone who has only thin galleys could never accept the battle, because it is sure that, since it is convenient to use this vessel [the large one] for that enemy, he would never reach the enemy; and if

[63]"che modo si deve tenere per rimediare al mancamento che hanno le galee grosse nella vuoga si che si possano in occasione vuogar senza remurchio," "se si devono allargar le postizze ad esse Galie," "che qualità de remi, et di che longhezza sara necessario adoperare," "se si devono accommodar esse galee à doj remi per banco, o, à uno," "La spesa che potesse andar in detto accommodamento," "Il modo di cavar poi esse galee dall'Arsenal in caso che si dovesse allargar le postizze," "Discorrendo oltra di cio intorno a tutto quello di piu, che gli paresse poter esser di pubblico servitio" (Contarini 1592–1593, 1v). Author's enumeration.

[64]The masters of the Arsenal and its executive body, constituted of Lords and Commissioners, distinguished between large galleys for trade and those for military purposes. In detail, the galleys for trade were "rounder," that is, a little bit wider than those destined for the military fleet. However, it was no rarity for trade galleys to be armed and sent as part of the military fleet or *vice versa*.

> one has the navy constituted of thin and large galleys, it will be useful for him to tow them always, since one is sure that he cannot win only with thin galleys unless they are of the same number as the enemy ones. and in order to address this lack, it will be prudent to use this sort of ships [large galleys] upon the condition that their imperfections are removed.[65]

Unless the dimensions of the military fleet constituted of thin galleys were increased, and this was impossible for the Arsenal of Venice at the time because of the lack of material, the use of large galleys would have been unavoidable. But if the imperfections which made it necessary to tow them had not been solved, such galleys could have been more a reason for military failures than a help for victorious conclusions.

Understanding why a particular model of ship could not be pushed forward by means of its own propulsion, especially within a tradition of centuries of successful shipbuilding like that of the Venetian Arsenal, was no trivial issue. Whether it depended on general or particular design issues, or construction techniques, or choice of materials, or rowing unit construction or position, it was a very puzzling problem indeed. Seventeen years after the battle of Lepanto, however, its cause was better determined and the inquiry to find a solution initiated. As implied in point 1. of the inquiry, the necessity of towing the large galleys was supposed to be a consequence of a design problem related to the dimensions of the superstructures of the vessel, and perhaps to those of the rowing unit constructions built upon them and, in turn, with the oars—their quality, length and number per bench.

Contarini opened the inquiry by repeating the points upon which he consulted with Galileo:

> [. . .] one has therefore to consider the instrument which makes her [the ship] go, which are the oars, as well as the force of the man who has to use those oars. For as concerns the oar which is used at present, it is not proportioned to the ship [. . .], which, if she [the ship] had larger superstructures could be given more [longer] handle, and consequently a longer pole, which would find the water far away from the ship, and so the oar would move slower and the force that the man would need to apply would be natural, because it would not deviate from the path followed by pulling to the breast and one could also place more men there [. . .]. Thanks to this remedy, there is not a single expert who cannot understand that one would provide a solution to this hindrance of the slowness by making this ship go, if not so well as the good thin galleys, at least as well as the mediocre ones, without which [the thin galleys] one could never advance, and never offer their service without being towed, and to

[65] "[. . .] si puo dire che possano esser un altra volta piu tosto di impedimento che di aiuto [. . .] non potendo star dredo una armata sotile senza esser remurchiati, possono esser causa per questo di tardanza di far perdere infinite occasioni buone. et chi havera galee sotil solamente potria a sua voglia non accettar mai la battaglia essendo sicuro, che l'inimico che conveniva valersi di questo vassello dovendolo remurchiar non lo arivara mai; et havendosi armata composta di galee grosse et di sotili si convenira star sempre sul remurchio, essendo sicuri di non poter vincere con l'armata di galee sotili solamente che non saranno per numero come quelle dell'inimico. et per proveder a questo mancamento sara sempre prudenza valersi di questa sorte de navilij grossi quando se gli levino quelle imperfezioni" (Contarini 1592–1593, 7r).

position them at the appropriate locations thanks to their own [propulsion], and to perform really great operations. [66]

Galileo's letter is evidently especially concerned with point 1.1. In fact, one of the solutions that the inquiry suggested addressing was the possibility of enlarging the superstructures of the ships, on whose sides the thole pins of the oars were positioned. Thus, Contarini was probably wondering whether, by enlarging only these, and without changing the rowing units, the oars or the number of oarsmen, they could expect some advantages. Indeed, this would have been the cheapest solution; point 1.3. of the inquiry signifies the relevance that the amount of expenditures entailed in the suggested solutions were required to have. Unfortunately for the treasuries of the Arsenal, however, Galileo was right in at least one point. Enlarging only the superstructures while leaving the rowing unit unchanged would not have affected the amount of propulsive force applied.

Definition of the problem The masters of the shipwrights (*Proti dei Marangoni*) were charged with supervising the construction of the ships. Because of their knowledge, experience and authority, their testimonies were considered to be of supreme importance. The first master of the shipwrights, interrogated by the delegate and nobleman Mocenigo during a meeting of the Committee dedicated to the inquiry, defined the problem clearly in the following terms:

[. . .] since the door of the Arsenal is narrow we are obliged to settle the measure of the superstructures not according to the mouth[67] of the galley, as one should do, if one wants to work in a good way: but because of the narrowness of the door, the superstructures in use now have a relevant problem such that one cannot use them [the galleys] as one would like to do on certain relevant occasions because of the shorter handle they have now [. . .].[68]

[66] "[. . .] s'hanno da considerar cosi l'instrumento che lo fa caminare, che sono i Remi, come la forza dell'huomo che ha da adoprar essi Remi. Quanto al remo che si adopra al presente non è proporzionato al navilio [. . .] che se havesse le postizze più larghe si daria piu ziron, et per consequenza piu asta, la qual trovaria l'acqua lontana dal navilio, et il Remo andarebbe piu piano, et la forza che bisognasse che l'huomo vi ponesse sarebbe naturale, perche non passarebbe al tirar il petto, et si potrebbono anco metter piu huomini [. . .]. con questo rimedio di allargar le postizze non è alcuno intendente che non conosce che si provvedera a questo impedimento della tardanza facendo caminar questo navilio, se non tanto quanto le galee sotil buone, almeno quanto le galee mediocri, senza le quali non si potra mai andar avanti, et potranno servir senza remurchio, et mettersi alli sui luoghi da se stesse, et far grandissime operazioni" (Contarini 1592–1593, 7r). In this document, which starts at folio 6v and ends at folio 7v, and from which this quotation is extracted, the author is not cited. But two reasons suggest that this text was the one proffered by Contarini at the *Collegio della Milizia da Mar* of Venice: first, because it is the only writing collected by Contarini that does not bear any name; second, because both of the deeply significant similarities between Contarini's reply to Galileo and this document, and of the presence of points like, for example, the one concerned with the movement of the oarsmen, which are not to be found in any other text submitted on the occasion of the inquiry.

[67] The mouth of a galley was the width of the ship measured midships above deck.

[68] "[. . .] essendo la porta dell'arsenale stretta semo di necessita di a far la mesura delle postizze non dalla bocca di essa galia come si doveria far a far ben: ma dalla strettezza della porta del Rastello, onde sono uscite dette postizze con difetto d'importanza non potendogli con così poco ziron come

Shipbuilding method Every kind of ship and boat was built according to a traditional set of ratios among the measures of their main components. Once the longitudinal length of the ship was decided upon, for instance, all other main measures, including the width, the superstructures, the handles of the oars and so on, could be calculated by simply applying the appropriate set of ratios. The situation concerning the large galleys presented problems even more serious than the ones discussed by Contarini and Galileo: Not even the traditional ratio between the mouth of the galley and the handle of the oar was respected.[69] Because of the narrow door of the Arsenal, the large galleys were equipped with superstructures that were narrower than what their appropriate and traditionally given set of ratios required. Morever, the dimensions of the mouth of the galley also determined the length of the handles of the oars. The handles were therefore shorter than prescribed by the traditional rules. The handle, in turn, was the term of comparison for the entire length of the oar: the ratio between the handle and the entire oar had to be 1:3. For this reason point 2. of the inquiry requests an opinion about a way to bring the galleys out of the Arsenal if they were to be built with those superstructures prescribed by the traditional building ratios. The master of the shipwrights agreed with Contarini. The problem of the galleys was represented by their oars, because they, that is, their handles, were too short.

The entire inquiry contains twenty-two written answers and the subsequent protocols and deliberations of the Committee. No opinion expressed in those delivered documents is in disagreement with the master of the shipwrights. All of them wanted the large galleys to be equipped with wider superstructures to make longer handles possible.[70]

---

portano al presente adoperarsi come bisognarebbe nelle occasioni d'importanza [...]" (Contarini 1592–1593, 2v).

[69]Contarini's last letter indeed already contains the suspicion that the propulsion problem of large galleys depended on an erroneous ratio between the mouth of the ship and the length of the handles of the oar. On that occasion, however, Contarini did not further analyze this point.

[70]The inquiry also investigated whether it would have been better to substitute the rowing unit equipped with one oar with another equipped with two of them. Although the opinions directly concerned with this point of the inquiry will not be taken into consideration here, the following brief explanation of this issue could be helpful for the general understanding of the way the Venetian shipbuilders worked. According to the traditional sets of ratios governing shipbuilding activity in Venice during the sixteenth and seventeenth centuries, a rowing unit equipped with one oar per bench of a certain and given length could be substituted by a different rowing unit with two or more oars, whose lengths were a certain ratio of the oars designed for a rowing unit with one oar. However, since in multiple-oar rowing units other factors had to be altered, such as the height of the benches, the Venetian masters of the Arsenal did not have any rule to foresee whether the two corresponding rowing units, the first equipped with one oar and the second, for example, with three, would effectively perform the same propulsive force. This was the main reason why the few masters who faced this opportunity remained conservative, suggesting that one large galley be prepared with a rowing unit equipped with two oars so that this construction could be tested. All other documents submitted propose retaining the rowing unit with a single oar per bench. First, because it meant lower costs in terms of the carpentry, material and screws needed and, second, because of the need to leave more space on the ship free for artillery and soldiers.

The problem of the "longer oar" Enlarging the superstructures of the galleys would have meant providing the galleys with longer oars. This operation, therefore, definitely involved considerations about the resistance of the oar. Galileo, who had already constructed the theoretical framework concerned with the cantilever model while discussing with Contarini how the oars functioned, found among the masters of the Arsenal the knowledge he needed to determine the ratio between the dimensions and weight of a solid body that define its resistance to fracture.

The Committee decided to experiment by changing the superstructures on one large galley already present at the Arsenal, which required new superstructures anyway because the old ones had rotted. Since it was a large galley built for trade and, therefore, had a mouth of 24 Venetian feet, the handle of the requested oar had to be 12 feet and the whole oar 42 feet, amounting to almost 14.6 meters! Since no large galley had ever been built according to the traditional set of ratios concerning the handles of the oars, and since these ships were the largest ships ever built in the Arsenal, the problem was that the shipwrights had no experience with oars of the requested length, for the simple reason that such oars had never been built. The inquiry therefore first had to investigate whether there was material at hand that could somehow prove useful for this purpose.

The written documents that have survived testify clearly to the institution's embarrassment in the face of this seemingly less significant technical challenge. But it was far from easy to provide a fitting solution. The first reason was the chronic difficulty the Venetians had in procuring material for shipbuilding, especially due to the loss of the Balkan territories, their main source of wood, after the Ottomans became established in the Balkan regions close to the Adriatic coasts.[71] In particular, the Arsenal did not have any warehoused oarage long enough to make the desired oars. Further, with one exception, all of the persons interrogated agreed that none of the forests at the Republic's disposal could supply the requested oarage. Therefore the only practicable solution was to use oars that had already been prepared, by attaching a piece of wood to the side of the handle in order to achieve the desired length.

None of the documents produced by the inquiry mention a word about the method used to join the poles together. The masters who were asked for their opinion as to whether such joints would have been resistant enough did not seem to have any trouble with it. However, this was not the case with regard to their opinions about another problem that was a consequence of this joining together pieces of oarage, namely, that the thickness of the oars would not have been changed. In particular, since the oars stored at the Arsenal had a length of 36 Venetian feet (just over 12.5

[71] The Ottomans' conquest of the Balkan region started very early in the fifteenth century, but did not begin to affect the Venetian economy seriously until after the Venetian military defeat at Corinth in 1465. Although the conquest continued to the doors of Vienna, the peace treaty between the Ottomans and the Venetians, signed in 1479 and then ratified in 1503, ensured the Venetians some of the materials needed from the Balkan woods through commercial trading with the Ottomans. This was no longer the case toward the end of the sixteenth century, however, so that materials were provided from regions which belonged to the Republic and were located on the Italian peninsula, in particular from those regions known today as Friuli and Venezia-Giulia.

meters),[72] the joint method meant that the Arsenal masters would have to lengthen the oars by more than two meters while maintaing the same thickness. This was a serious point of contention. Contarini's register reports eight opinions *contra* and seven *pro* the joint solution because of this aspect.

On March 16, 1593, a few days before Galileo wrote, Nicolò Balbi, a delegate of the *Collegio della Milizia da Mar*, submitted his written opinion after an exploratory visit to the Arsenal, stating that:

> [...] if the superstructures are enlarged toward the outside by only one foot, one should consequently lengthen the oarage so that the [oar] 36 feet long would become 40 feet and that of 38, then 42, which would become so weak that with a little bit of exertion, or a slightly greater number of people, it would break, or the handle would come to the breast of those who row it, [and] therefore nothing good could be made, because the oarsman would have more effort in making himself free from the impetus of that handle from the breast than being applied in rowing, as is very well known to all those who are expert in this profession. Not to mention that, every storm on the sea, and every little bit of effort they had, would break the oars into [several] parts.[73]

Here Balbi took into consideration the possibility of joining a pole to the handle of the stored oars, but considered the resulting oar too weak. However, Balbi did not limit himself to a mere criticism of this solution. He also considered the possibility of sawing brand-new oars of the desired measures, could the needed wood have been found. He specified that:

> If one wants to let them saw with that length in the wooden of the Archduchy, one should let them remain so thick, and heavy, that not four men, and not even six would be able to use them, neither for long [time], nor for short [time].[74]

In conclusion, Balbi seemed to have found a true practical, or even structural, limit for shipbuilding with wood. He stated that if one wants to follow the traditional set of ratios, then large galleys should be built with decreased measures, as efficient oars 42 feet long would be so thick and thus so heavy that the number of oarsmen that would fit in a ship whose mouth was in the correct proportion to the handle of that oar would still be not able to row it.

Solution of the problem and the content of a new science Balbi's visit to the Arsenal must have been a very interesting one. It is impossible to extract more details about his investigation, like the specialization of the masters with whom

---

[72] 1 Venetian step = 1.738 m = 5 feet: 1 Venetian foot = 34.76 cm.

[73] "[...] tirando in fuora le postizze un sol piede, bisognarebbe sussequentemente slargar il palamento a tale che quello di piedi 36 verrebbe ad esser di piedi 40, et quello di 38 di 42, li quali [...], s'indeboliria si fattamente che ogni poco di sforzo, o di maggior numero de genti si scavazzaria, overo ch'el zirone veniria al petto di cui lo vogassero, per il che non potrebbe mai far cosa buona, et sendo che maggior sarebbe la fatica del galiotto nel liberarsi dall'impeto di esso ziron dal petto che non sarebbe quella del vogar, si come è benissimo noto a tutti quelli che intendono quella professione. Lascio da parte, che ogni borasca da mare, et ogni poco di straccolo che havessero andarebbero tutti in pezzi" (Contarini 1592–1593, 9v).

[74] "Volendone mo far tagliar di quella longhezza nelli boschi de Arciducali, bisognaria farli tenir si fattamente grossi, et pesanti, che non solo 4 huomini, me ne anco sei potranno, ne per molto, ne per poco adoperarli" (Contarini 1592–1593, 9v).

he spoke and what they showed him. However, a good idea of how Balbi's visit took place can be pieced together on the basis of another testimonial collected in Contarini's register. This evidence is particularly relevant not only because of its content, but also because of the person who has given it: the master of the oar makers (*Proto de Remeri*), in charge of the production of oars at the Arsenal, and therefore the most representative voice from the front of the practical knowledge concerning oars.

Upon interrogation in March 1593, the *Proto de Remeri* Christoforo de Zorzi gave a precise report about the measures and numbers of the oars currently warehoused, clearly pointing out not only that there were no oars 42 feet long, but, in particular, that if the joint solution had been chosen, the oarage at disposal would have sufficed for very few galleys. But then, in the written document submitted, in consideration of the joint method to obtain oars 42 feet long, he first added that:

> [. . .] if one makes the oarage greater it will happen that it will be longer, and as the Oar will be greater it will have no force, because it will be tender, and will make it impossible for the galley man to row, because the handle will hit him on the breast; [. . .].[75]

Neither did the master in charge of oar production like the solution represented by the joint method. Instead of taking into consideration the eventuality of finding the right wood for longer oars, however, he made some suggestions about the lengths which can be obtained by using the joint method with the oarage already at hand in order to avoid the problem of the weaker oar:

> [. . .] but one can well change the galleys which are there at present[:] but that which has an oar of length of 36 feet, and a handle of 12 feet can be changed so that it has an oar of 39 feet and a handle of 13, and that which has an oar of 38 feet and a handle of 12 [and] 1/2 feet can be changed so that it has an oar of 40 feet and thus a handle of 13 [and] 1/3.[76]

Mr. de Zorzi was equally unconvinced of the practicability of making 42-foot oars. However, he determined the exact length to which the warehoused oars could be extended using the joint method, and did so in a very interesting way for two different kinds of oars, 36 feet long and the other 38, and further presented two correspondent measures which, compounded with the original lengths of the oars, do not amount to any linear proportionality. Whereas the 36-foot oar could be lengthened to up to 39 feet, that is, a three-foot pole could be added to it, in reference to the other oar, 38 feet long and certainly thicker than the first, at most a 2-foot long pole could be joined. Although these numbers do not agree with the rules later given by Galileo in his *Discorsi*, they certainly show that the master of

---

[75] "[. . .] facendole maggiori il palamento convenira esser di maggior longhezza et come il Remo sara maggiore non havera forza, che sara tenero, et fara che il galiotto non possa rogare, che il ziron li dara nel petto [. . .]" (Contarini 1592–1593, 4v).

[76] "[. . .] ma ben si potra accomodar le galie che sono in esser al presente quella pero che ha il remo de longhezza de piedi 36, et il ziron sia pie 12 se potra accomodarle che habbi il remo de pie 39 che havera il ziron de pie 13, et quella che ha il remo de pie 38 che ha il ziron de pie 12 1/2 si potra accomodarla che habbi il Remo de pie 40, che havera il ziron pie 13 1/3" (Contarini 1592–1593, 4v).

the oar makers knew perfectly that by increasing the length of the oar linearly, its thickness had to increase over-proportionally—and he could even quantify how.

Soon after his arrival in Padova, and thanks to his involvement in the official inquiry promoted by the *Collegio della Milizia da Mar* of Venice, Galileo not only generated the core idea of what would become his first new science, but even encountered a practical and quantified example of how this idea works. First, Galileo revolutionized the way to apply the lever model by considering the water, that is, the extremity opposite to the one where the moving force is applied, as the fulcrum. In fact, if the problem is no longer the propulsive force performed by the oar, but the resistance of the oar to fracture, then Galileo's words contained in his letter to Contarini—"fulcrum and resistance are the same"—took on a very precise meaning related to his cantilever model: Fulcrum and resistance are placed at the same point, where the cantilever is driven into the wall. Galileo in fact used the same concept and the same word—*resistenza*—to denote both the weight to be moved and the resistance to fracture. According to this view then, Galileo rightly suggested to Contarini that the handle of the oars be shortened. But in his reply Contarini taught Galileo that the same result must be obtained with long handles. Yet this solution was doomed by the problem of lacking material and the consequent practical considerations by the masters of the Venetian Arsenal, according to whom simply lengthening the oars would have presented a problem related to their resistance. The representatives of the practical knowledge of the Arsenal, that is the masters, the members of the administrative and organizational executive body of the Arsenal and the members of the Navy Committee of Venice, finally offered Galileo centuries of experience, constituted of not only qualitative statements, but even quantitative indications, which Galileo integrated into his new cantilever model.

Galileo's Masterpiece: The Oar Model

The cantilever model was useful to Galileo in reference to the way the oars work in order to establish the circumstances under which one could achieve the most efficient propulsion. This was when the handle is very short, the force is considered to be applied only at its extremity, and the blade is immersed deeply into the water. Eventually, due to the impracticability of such a model in the context of the way the rowing unit functioned, Galileo formulated a third model in the context of his science of materials. Under certain aspects, this final model seems to be an attempt to furnish a method of solving the problem of the "longer oar" that emerged during the inquiry.

Proceeding toward such a third model, which might be called "oar model," Galileo showed that a cylinder driven into a wall, the size of which is at the limit over which the cylinder would break, can be twice as long, keeping the same thickness, when it is removed from the wall and leaned on either one support at its middle point or two supports at its extremities. And then Galileo proposed to:

> [. . .] find whether the same force or weight which produces fracture when applied at the middle of a cylinder, supported at both ends, will also break the cylinder when applied at some other point nearer one end than the other [. . .] (*EN*, VIII:173).

Considering the necessity of long handles, Galileo considered a model which more closely resembles that of the oar, although it is not identical. According to this model, the cylinder is supported by one point in between the extremities and the force is applied at its ends. Indeed, this is almost the same model that allows the analysis of the resistance of an oar supported by a thole pin. However, for this model Galileo did not take into consideration the materiality of the cylinder, as he did in the cantilever model. Galileo did not consider the weight of the cylinder or oar itself. For this reason, although this model corresponds geometrically to that of the oar, it cannot be considered as a definitive answer to the doubts of the Venetian masters. In the case of the cantilever model, too, Galileo began his considerations by first disregarding the weight of the cylinder driven into the wall, but then integrating this data into the model so as to avoid addressing only the behavior of an ideal cantilever. In the case of the oar model, however, Galileo was no longer able to integrate this data and so proceeded by investigating how an ideal lever works in the case of the oar model. In this sense, to conclude, Galileo's answer to the *Proti* concerns only an ideal oar.

Translated into the language of the master of the oar makers, Galileo investigated how the resistance to fracture changes when the thole pin is not at the middle point of the oar, but positioned toward one of the two extremities, with the thole pin placed at a distance of one third of the length, measured from the handle end. Galileo searched for a general rule first, considering the case in which the support can be moved infinitely toward an extremity. He postulated that, if the support were shifted infinitely toward an extremity, the force needed to break the whole cylinder, which must be applied at that same extremity, must also increase infinitely; therefore (Fig. 4.5):

> [. . .] as the fulcrum F approaches the end D, we must of necessity infinitely increase the sum of the forces applied at E and D [the two extremities] in order to balance, or overcome, the resistance at F (*EN*, VIII:175).

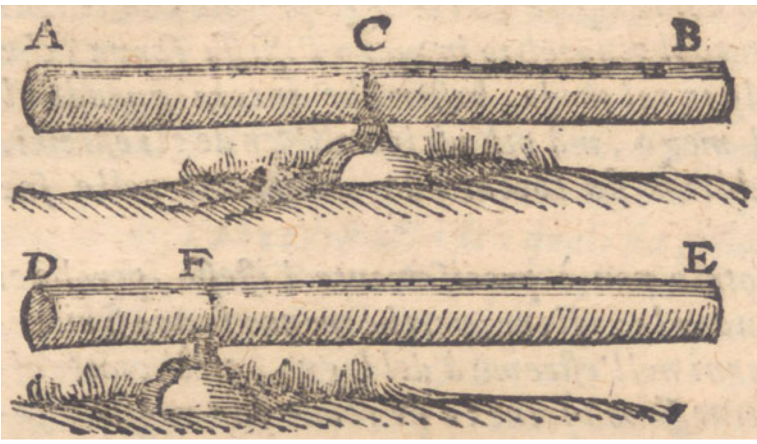

Fig. 4.5 Illustration of Galileo's oar model (Galilei 1655, 102)

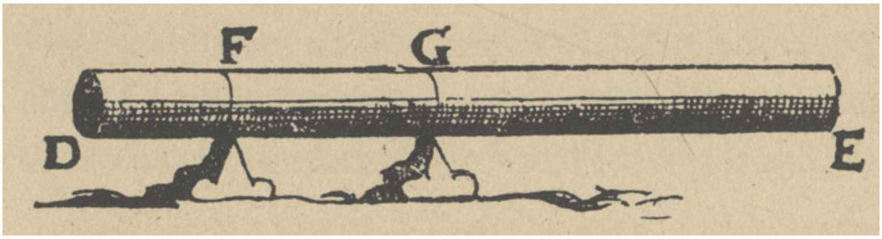

Fig. 4.6 Illustration to explain the behavior of the oar model (*EN*, VIII:176)

Since, however, the problem of the "longer oar" concerned the resistance of oars whose thole pin is placed at one precise point, in the *Discorsi* Galileo's Venetian friend Sagredo seems to ask Salviati for this specific solution:

> But it would be better if Salviati were to show us by just what proportion the forces must be increased in order to produce a fracture as the fulcrum is moved from one point to another along one and the same wooden rod (*EN*, VIII:175).

In the manuscript prepared by Galileo to try to have the *Discorsi* printed in Prague and sent to Giovanni Pieroni, Galileo added an explanation by his own hand, which ultimately was not included in the final version, although it would have improved the understanding of the text, possibly because its inclusion would have required preparation of an additional illustration (Fig. 4.6). This explanation offers the solution sought by Sagredo by using the oar model, proceeding by comparing two cylinders of the same dimensions but whose supports are displaced at two different points:

> If upon a cylinder one marks two points at which a fracture is to be produced, then the resistances at these two points will bear to each other the inverse ratio of the rectangles formed by the distances from the respective points to the ends of the cylinder (*EN*, VIII:176).

Galileo's answer is only partially satisfactory. First, because it does not consider the cylinder's own weight. Second, and more importantly, because the *Proto* would have probably preferred to know a way to compare two oars of different lengths—one with which he had lifelong experience, and the other with which he was not familiar—than two equal oars with fulcra displaced at different points. Moreover, Galileo also disregarded Contarini's view of the oar, according to which one cannot consider the force as being applied only at the extremity of the pole on the handle end, but rather at the number of points represented by the hands of the oarsmen. This is relevant not only for the explanation of how the oar functions, but also for the determination of its resistance.

Did Galileo Become a *Proto*?

Galileo's masterpiece was not a success. It certainly would not have sufficed for him to become a master. However, it provided him with the opportunity to found a new science of the strength of materials. The contact with the practical knowledge that proved so fruitful for the foundation of the first new science took place in the Venetian Arsenal; the professionals involved were shipbuilders; and the questions discussed concerned primarily shipbuilding and the functioning of the ship as a propelled mechanical device. However, Galileo's first new science was first perceived as an attempt to found a science of the singulars, that is, a science able to take into consideration all irregularities and accidents of each kind of material, or even of each solid body. The strongest opposition, on the basis of this perception, came particularly from engineers and craftsmen like the machine makers. This apparent paradox arose because Galileo superseded the Aristotelian vision, which was shared by most of the engineers, on the basis of the practical knowledge of the Arsenal.

Galileo used the *Mechanical Questions* as a sort of tabular research program to be accomplished by visiting the Venetian Arsenal and investigating the work, methods and accumulated experience of the shipbuilders. It has been already shown (Valleriani 2009a) how the first early modern theory of the strength of materials was the result of a process of integrating the practical knowledge of the architects into the Aristotelian arguments of Questions 14 and 16 of the *Mechanical Questions*, namely of those arguments related to the resistance of materials and the cantilever model. Galileo's first new science is, in turn, the result of integrating aspects of the practical knowledge of the Arsenal into the early modern Aristotelian theory of the strength of materials. Galileo's first new science, therefore, is not merely founded in the practical knowledge Galileo shared at the Venetian Arsenal, as if this theory had suddenly occurred to him while visiting the shipyards. Among the shipwrights Galileo found knowledge that challenged the Aristotelian doctrine, that is, the only theoretical approach that Galileo had at his disposal to start with. In conclusion, the generation of new theoretical knoweldge is the result of the investigations of an Aristotelian engineer.