The Transformation of Aristotle's Mechanical Questions: A Bridge Between the Italian Renaissance Architects and Galileo's First New Science

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Summary

The reception process of Aristotle's Mechanical Questions during the early modern period began with the publication of the corpus aristotelicum between 1495 and 1498. Between 1581 and 1627, two of the thirty-five arguments discussed in the text, namely Question XIV concerning the resistance to fracture and Question XVI concerning the deformation of objects such as timbers, became central to the work of the commentators. The commentaries of Bernardino Baldi (1581–1582), Giovanni de Benedetti (1585), Giuseppe Biancani (1615) and Giovanni di Guevara (1627) gradually approached the doctrine of proportions of the Renaissance architects, some aspects of which deal with the strength of materials according to the Vitruvian conception of scalar building. These aspects of the doctrine of proportions were integrated into the Aristotelian arguments so that a theory of linear proportionality concerned with the strength of materials could be formulated. This very first theory of strength of materials is the theory to which Galileo critically referred in his Discorsi where he published his own theory of strength of materials. Economic and military constraints are determined as the fundamental reasons for the commentators' commitment to developing a theory of strength of materials that later linked Galileo's work to the practical knowledge of the architects and machine-builders of his time.

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1. Introduction

From the beginning of the sixteenth- until the mid-seventeenth century the reception process of Aristotle's Mechanical Questions[1] was particularly intensive. Humanists as well as mathematicians and practitioners produced a great number of translations, paraphrases, commentaries and notes on this most authoritative ancient scientific work.[2] A number of studies[3] have already shown that the reason for the practitioners' interest in the Aristotelian work was not an aspiration to improve their social and scientific status by having their names written alongside this great philosophical and scientific authority. To this conclusion it might be added that rather the opposite happened. The social status of practitioners was improving regardless, particularly for those whose work was connected to the early modern development of the military arts.[4] Because of the practitioners' increasing relevance in the economical, political and cultural fields, they were urged to present their works, their skills and themselves not only by their actions, but also by using the only medium they had at hand: written texts and drawings. The entrance into higher social networks, such as the court, obliged them therefore to codify and systematize their knowledge. This process led them to explore the theoretical foundations of their arts and methods. In the frame of this search for explanatory models, Aristotle's Mechanical Questions represented only one of several texts they had at their disposal. The Aristotelian text, however, became extremely popular during the early modern period.

The learned and inquisitive men of the Renaissance were particularly impressed by the advanced status of certain fields of practical activity. Buildings like the Cupola of Santa Maria del Fiore in Florence and the machines operating on such building sites, the Venetian large galleys and sea-bound ships, extremely elaborate aqueducts and a new generation of pneumatic devices, like those built in the Garden of Pratolino,[5] were not only impressive but also represented a challenge for mathema-ticians and natural philosophers, whose theories, for example on statics, were not always able to explain satisfactorily the methods of the architects and the engineers

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1 Aristotle, 'Mechanical problems', in Aristotle: in twenty-three volumes, edited by W.S. Hett (Cambridge, MA, 1980 reprinted ed.), Vol. 14, Minor works, 331–411. Due to the need for a deeper analysis of Aristotle's text, the fifth section of the present work uses a different translation which was accomplished within the framework of a workshop organized by the author. For more details, see footnote 43.

2 P.L. Rose and S. Drake, 'The Pseudo-Aristotelian Questions of Mechanics in Renaissance Culture', Studies in the Renaissance, 18 (1971), 65–104, and W.R. Laird, 'The Scope of Renaissance Mechanics', Osiris, 2 (1986), 43–68.

3 J. Renn, 'Mentale Modelle in der Geschichte des Wissens: auf dem Weg zu einer Paläontologie des Mechanischen Denkens', Dahlemer Archivgespräche, 6 (2000), 83–100; P. Damerow, J. Renn, S. Rieger, and P. Weinig, 'Mechanical Knowledge and Pompeian Balances', in Homo Faber. Studies on Nature, Technology, and Science at the Time of Pompeii, edited by G. Castagnetti, A. Ciarallo, and J. Renn (Rome, 2002); J. Büttner et al., 'The Challenging Images of Artillery*Practical Knowledge at the Roots of Scientific Revolution', in The Power of Images in Early Modern Science, edited by W. Lefèvre, J. Renn, and U. Schoepflin (Basel, 2003), 3–38.

4 M. Biagioli, 'The Social Status of Italian Mathematicians, 1450–1600', History of Science, 27 (1989), 41 95.

5 For more details about the reception of ancient pneumatics and its relation to the Garden of Pratolino, see M. Valleriani, 'From Condensation to Compression: How Renaissance Italian Engineers Approached Hero's Pneumatics', in Übersetzung und Transformation, edited by H. Böhme, C. Rapp and W. Rösler (Berlin, 2007), 333–54. M. Valleriani, 'The Transformation and Reconstruction of Hero of Alexandria's Pneumatics in the Garden of Pratolino' in Pratolino. A Myth at the Gates of Florence, edited by L. Ulivieri and S. Merendoni (Venice, 2008), 155–81. See also L. Zangheri, Il giardino delle meraviglie (Florence, 1987), 2 Vols.

or the functioning of their creations. The attention given to practical knowledge therefore increased during the early modern period; the Renaissance theoreticians thus aimed to provide theoretical fundaments for the practical outputs, or to present them as results on which their theories could rely.[6] The commentators on Aristotle's Mechanical Questions of the sixteenth century remained committed in this way to practical knowledge and were thus involved in an ongoing process of sharing their work with that of the practitioners.

The commentators on Aristotle's Mechanical Questions searched for an explana-tory model of aspects of practical knowledge and experience within the Aristotelian arguments. This means that they did not simply translate the text, for example, into Latin or Italian. They rather reflected on their own practical knowledge and skills, codified them and at the same time desegregated, reinterpreted and reconstituted the Aristotelian arguments in an attempt to merge those two different knowledge fields and models in the most consistent way possible. At the end of this process both knowledge frames turned out differently or, to put it more appropriately, were transformed. This process took place both diachronically and synchronically: while single figures, for example architects or commentators who may be termed 'agents of the transforma-tion', produced a new and transformed edition of Mechanical Questions, the work of each agent was then further elaborated by other single agents of the transformation. In other words, the process of transformation is constituted by several performative steps which can be seen as a whole only from the historical perspective.[7]

This outline of the process of the transformation of ancient science as being due to an attempt to apply the theoretical foundations of an ancient scientific text to the various practical problems of a different era, such as the early modern period, during the reception process of the same text, is achieved with the analysis of the following historical case.

It is usually asserted that the first scientific theory of the strength of materials is the one formulated by Galileo and published in 1638 in his Discorsi e dimostrazioni matematiche intorno à due nuoue scienze as the First New Science.[8] According to this

[6] Galileo's formulation of the trajectory of projectile motion, for example, is rooted in the practical knowledge of the artillerists of his time. For more details, see J. Renn, P. Damerow, and S. Rieger, 'Hunting the White Elephant', in Galileo in Context, edited by J. Renn (Cambridge, 2001), 29–152. See also Büttner et al., 2003 (footnote 3).

[7] In 1986 Roy Laird convincingly showed how early modern commentators on Aristotle's Mechanical Questions were engaged in a process of 'boundary negotiations' which redefined the identity and scope of Renaissance mechanics in relation to practical mechanics and natural philosophy. The step-by-step process of transformation outlined here and in the following case study can be seen as an attempt to show how such a process of negotiation could function. For more details, see Laird 1986 (footnote 2) and W.R. Laird, The Unfinished Mechanics of Giuseppe Moletti (Toronto, 2000), esp. 3–65.

[8] The Edizione Nazionale of Galileo's works, edited by A. Favaro, is used here: G. Galilei, Discorsi e dimostrazioni matematiche intorno à due nuoue scienze, attenenti alla mecanica & i movimenti locali, in Le opere di Galileo Galilei, edited by A. Favaro (Florence, 1968), VIII, 39–362. Galileo's science of the strength of materials, namely his First New Science, is not a major research field for the community of Galileo's scholars. For example, in the three-volume publication of Drake, Swerdlow, and Levere of 1999 not one paper is dedicated to this topic. For more details, see S. Drake, N.M. Swerdlow, and T.H. Levere, Essays on Galileo and the History and Philosophy of Science (Toronto, 1999), 3 Vols. Drake however strongly asserted Galileo's scientific primacy in the field of the theory of strength of materials in G. Galilei and S. Drake, Two New Sciences, including centers of gravity & force of percussion (Madison, WI, 1974), 15, footnote no. 7. This thesis is moreover implied in D. Bertoloni Meli, Thinking with Objects: the Transformation of Mechanics in the Seventeenth Century (Baltimore, MD, 2006), 93. The thesis of Galileo's supremacy is particularly common in the field of the history of architecture. See, for example, S. Di Pasquale, L'arte del costruire (Venice, 1996) and E. Benvenuto, La scienza delle costruzioni e il suo sviluppo storico (Rome, 1981), English ed. 1991; 2nd Italian ed. 2006.

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view, before this theory was published, knowledge about the strength of materials corresponded to the practical experience codified within the conceptual frame of the building methods of the architects. Sets of rules to be followed while building something like a house, a vault or a machine contained more or less surreptitiously all the information needed to deal with the issue of strength of materials. These practical rules indicated how a certain object had to be built, for example, when passing from the model of a machine to its actual construction. However, there was no explanation given for them; they were not reduced and explained on the basis of a principle. These rules taken together did not correspond to or include any theory. They represented the 'doctrine of proportions' of the architects.[9]

This work aims to show that before Galileo published his First New Science, another theory dealing with the strength of materials had already been formulated and, in particular, that this very first theory was the result of a process of theoretization of the knowledge of the practitioners and of those aspects of their doctrine of proportions that are related to the issue of strength of materials. Such a process was carried out by the commentators on Aristotle's Mechanical Questions. Practitioners and commentators integrated these practical rules into the Aristotelian arguments, which, being deductively based on the principle of the lever, became a theoretical fundament. This process, which took place between 1581 and 1627, consequently transformed the Aristotelian arguments in the way they were conceived and presented in the commentaries of those years. In this way the 'theory of linear proportionality' concerned with strength of materials emerged, to which Galileo critically referred in his Discorsi and by means of which Galileo's theory is linked to the practical knowledge of the Italian Renaissance architects.

2. The doctrine of proportions

The doctrine of proportions is a set of practical rules used by ancient and early modern architects when designing and planning a building.[10] During the early modern period the doctrine of proportions was elaborated on the basis of the reception process of Vitruvius' treatise on architecture.[11] Within the Vitruvian frame the doctrine of proportions is needed to achieve three major goals. The building to be designed and built must be stable and resistant (firmitas), comfortable (utilitas) and, finally, it should also satisfy the aesthetics of the time (venustas). Concerning the venustas, the doctrine of proportions determines the

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[9] The definition 'theory of proportions' is generally used in English papers, as well as, for example, 'teoria delle proporzioni' in Italian ones. However, the same scholarly works also typically assert that the theory of proportions was not a theory but rather a set of practical rules. In the first chapter of his book entitled 'Knowledge without theoretical fundaments', Salvatore di Pasquale, for example, describes the 'theory of proportions' of the architects (Di Pasquale, 1996. footnote 8). Thus, following the more appropriate German definition 'Proportionslehre', the definition 'doctrine of proportions' will be used here.

[10] The content of this section and of section 7 draws substantially on Di Pasquale 1996 (footnote 8). Although Di Pasquale does not differentiate sharply between the theories of the commentators on Aristotle's Mechanical Questions and the doctrine of the architects, his book is probably the best available work at the moment for the description of the latter topic. Di Pasquale also published a contribution in English concerned with the art of building before Galileo's time: S. Di Pasquale, 'On the Art of Building before Galileo', in Between Mechanics and Architecture, edited by P. Radelet de Grave and E. Benvenuto (Basel, 1995), 103–21.

[11] The following English translation of Vitruvius' De architectura is used here: P. Vitruvius, I.D. Rowland, T.N. Howe, and M. Dewar, Vitruvius: Ten Books on Architecture (New York, 1999).

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symmetry of the entire building according to the ancient meaning of the term 'symmetry'.[12] It determines, for example, the length of the façade in relation to that of the sidewall and to the entire height, or the number of columns in relation to their length and to the façade. These are therefore rules concerned with the appearance of the entire building and so with the way the building can be perceived as a whole. Concerning the utilitas, the doctrine of proportions governs, for example, the number of rooms given the total amount of space available, the size of each room given their number, and according to their function, the size of their entrance or of other features. The Vitruvian firmitas refers to both the modern issues of stability and resistance of a building. Using Di Pasquale's example,[13] there is a problem with stability when a column falls because of a horizontal force applied at its top; there is a problem of resistance when, for example, a cantilever driven into a wall breaks off due to a weight being hung from the opposite end. Concerning the firmitas, the doctrine of proportions has rules which in principle were able to guide the architect during the design and building process in such a way as to avoid total or partial collapse.

All of the practical rules concerned with firmitas, utilitas, and venustas were considered to be a unique doctrine for they were all based on the same building conception: Vitruvian architecture was modular, that is, a basic unit of measurement* modulus*was chosen as a term of comparison for all other dimensions of each architectural component, of each system of components and finally of the whole building. In the case of Vitruvius, using the example of sacred temples, the basic unit of measurement was the thickness of the main columns at their base.[14] Each single architectural element of the sacred temple therefore required dimensions defined in relation to the measure of the thickness of the main column at its base, and all of the rules constituting the doctrine of proportions could be expressed in form of ratios between measurements of architectural elements and the modulus.

According to the conception of modular architecture, if one and the same building is built twice but with different dimensions, the architectural elements of the larger building are, taken singularly, also larger in exact agreement with the ratio between the dimensions of the moduli taken for the two buildings. Modular architecture thus determines a scalar building method. This method is also concerned with stability and strength so that the two similar buildings mentioned should also be equally stable and resistant.

Implicitly the argument can be reduced to the consideration of one single component such as a raising block. Against the background of the doctrine of proportions, if there are two raising blocks that ideally differ from each other only in their dimensions, and if their lengths, heights and depths are linearly proportional,

[12] In 1567, Daniele Barbaro wrote in his commentary on Vitruvius: '[. . .] the Symmetry is a uniform consent among the limbs of the same work and a correspondence of each of them, taken singularly, to the entire figure, according to the appropriate proportions' ('[. . .] la Simmetria è un accordo uniforme tra i membri della medesima opera, ed una corrispondenza di ciascuno de' medesimi, presi separatamente, a tutta la figura intiera, secondo le proporzioni che le compete'). From P. Vitruvius, D. Barbaro, M. Tafuri, and M. Morresi, I dieci libri dell'architettura (Milan, 1997), I, 4. See also Di Pasquale 1996 (footnote 8), 44–45.

[13] Di Pasquale 1996 (footnote 8), 90–91.

[14] Vitruvio, Barbaro, Tafuri, Morresi 1997 (footnote 12), I, 4. See also Di Pasquale 1996 (footnote 8), 45.

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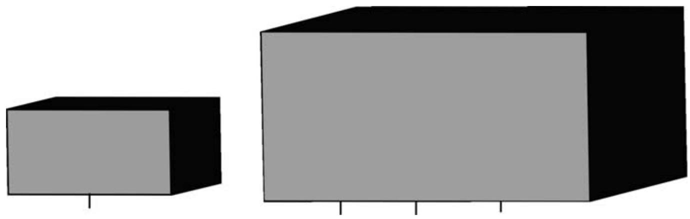

Figure 1. Scalar increase of a raising block.

then these raising blocks should have the same resistance to fracture. In practice, if one is given a stable raising block whose height and depth is 1 m and whose length is 2 m and one requires a new block with the same resistance to fracture but 2 m high, then according to the general conception of Vitruvian modular architecture, the new block would have to be 2 m in depth and 4 m long (Figure 1).

This extrapolated aspect of the doctrine of proportions will be taken into consideration in the following and will be called here the 'doctrine of linear proportionality' concerned with the strength of materials. Architects and practi-tioners were followers of the doctrine of linear proportionality and did not acknowledge any conceptual difference between the phenomenon of deformation, for example bending, and that of fracture. In modern terms, they considered their objects to be infinitely rigid. As such, their implicit definition of the strength of an object must have been based on the use of two parameters: the first parameter is the thickness, which is that dimension of the side of the object against which a force acts; the second parameter is the dimensions of all of the sides of the same object, excluding its thickness. Taking a cylinder placed horizontally, fixed at one end and with a weight hanging on the opposite end, its diameter would be the thickness, and its length the second parameter.

In conclusion, the doctrine of proportions implicitly contained the doctrine of linear proportionality, which concerns the strength of materials and is based on a definition of strength that relates two parameters: the thickness and the length.[15]

Vitruvius' De architectura was extremely popular during the early modern period. The translation and commentaries published by Daniele Barbaro in 1567 are particularly well known.[16] But the mainstream reception of the ancient work began already in 1543 with Leon Battista Alberti[17] and continued during the entire sixteenth century thanks to the works of major Italian architects such as, for example, Sebastiano

[15] According to the shape of the objects the second parameter could be represented by more than one dimension. For the present argument this is irrelevant and for sake of simplicity the second parameter will be considered in the following only as the length.

[16] Barbaro published first in Italian in 1556. The 1556 Italian edition and the 1567 Latin edition are slightly different. For the Barbaro edition of 1567, see Vitruvio, Barbaro, Tafuri, Morresi 1997 (footnote 12).

[17] Alberti's work had been published already in 1485. For more details, see L.B. Alberti, G. Orlandi, and P. Portoghesi, L'architettura: De re aedificatoria (Milan, 1966).

Serlio in 1540[18] and Andrea Palladio in 1570.[19] This work does not aim to analyse systematically each of the treatises of these architects, which have been the subject of numerous researches, especially in the field of history of architecture.[20] However, it is relevant to point to the fact that these architects accepted and elaborated Vitruvian modular architecture and in doing so more or less implicitly agreed with the doctrine of linear proportionality concerned with the strength of materials.[21] Palladio, one of the greatest architects of the sixteenth century, wrote for example that:[22]

> To understand them [the orders of architecture] [. . .] one has to know that, while dividing and measuring the mentioned orders [. . .] like Vitruvius, who divides the Doric order on the basis of a measurement taken from the thickness of the column [. . .] and which he calls modulus [. . .] I will also use such a measurement in all of the orders. [. . .]. Therefore, everyone will be able to apply the proportions and the drawn templates conveniently to each order using a greater or smaller modulus according to the quality of the building.

Architecture is one of the fields whose output during the early modern period remains among the most impressive. The treatises of the mentioned architects codified and systematized knowledge that deeply influenced the whole cultural and scientific panorama up until the late Renaissance. Their doctrine of proportions and its implicit assumptions and consequences were widely accepted far beyond the limits of the single discipline of architecture. Galileo confessed in 1638 that he had adhered to this conception as a young mathematician.[23] He later changed his opinion in favour of his own theory of the strength of materials, namely his First New Science. This science, published in the Discorsi in 1638 and described in the First and Second

[18] Serlio's work is published in S. Serlio, I sette libri dell'architettura (Sala Bolognese, 1978). The first volume of his Regole generali was published already in 1537.

[19] A. Palladio, L. Magagnato, and P. Marini, I quattro libri dell'architettura (Milan, 1980).

[20] The literature on Renaissance architects is imposing. Apart from Di Pasquale 1996 (footnote 8), a good overview is given in the following contributions: Between Mechanics and Architecture, edited by P. Radelet-de Grave, E. Benvenuto (Basel, 1995; E. Benvenuto, 'Entre Méchanique et Architecture', 7–20; P.D. Napolitani, 'La géométrisation des qualités physiques au XVIème siècle: les modèles de la théorie des proportions', 69–88; S. Di Pasquale, 'On the Art of Building before Galilei', 103–22. See also the following series of case studies from Proceedings of the First International Congress on Construction History, edited by S. Huerta (Madrid, 2003, 3 Vols.: A. Ageno and M. Frilli, 'Architecture as talisman: The hidden links between Vitruvius' theatre and Palladio's villa «Rotonda»' 151–60; A. Becchi, 'Before 1695: The statics of arches between France and Italy' 354–64; S. D'Agostino, 'The ancient approach to construction and the modem project', 669–76; E. Giunchi, R, Malvezzi, M. Russo, C. Alessandri, and R. Fabbri, 'Wooden composite beams: A new technique in the Renaissance of Ferrara', 1023–32; G. Tampone and F. Funis, 'Palladio's timber bridges', 1909–20.

[21] For an extensive discussion about the doctrine of proportions see, for example, Book IX of Alberti's De re aedificatoria in Alberti, Orlandi, Portoghesi 1966 (footnote 17).

[22] The original Italian text reads: 'A intelligenza de' quali [. . . .] è da sapersi ch'io nel partire e nel misurare detti ordini [. . .] imitando Vitruvio, il quale partisce e divide l'ordine dorico con una misura cavata dalla grossezza della colonna [. . .] e da lui chiamata modulo, mi servirò ancor io di tal misura in tutti gli ordini. [. . .]. Onde potrà ciascuno, facendo il modulo maggiore e minore secondo la qualità della fabrica, servirsi delle proporzioni e delle sacome disegnate a ciascun ordine convenienti'. From Palladio, Magagnato, Marini 1980 (footnote19), 31 (author's italics).

[23] Salviati, Galileo's speaker in the Discorsi, says: 'For a while, Simplicio, I used to think, as you do, that the resistances of similar solids were similar; but a certain casual observation showed me that similar solids do not exhibit a strength which is proportional to their size, the larger ones being less fitted to undergo rough usage' ('Quello che ora accade al Sig. Simplicio, avvenne per alcun tempo a me, credendo che le resistenze di solidi simili fusser simili, sin che certa, nè anco molto fissa o accurata, osservazione mi pareva rappresentarmi, ne i solidi simili non mantenersi un tenore eguale nelle loro robustezze, ma i maggiori esser meno atti a patire gl'incontri violenti'). From Galilei 1968 (footnote 8), 164–65.

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Days, is able to show that the doctrine of linear proportionality concerned with the strength of materials is erroneous. As a consequence, when the architects of Galileo's time became aware of the content of his theory, they initially reacted with severe opposition to his results.[24] However, it is incorrect to assert that Galileo's theory of the strength of materials emerged as a direct reaction to the doctrine of proportions of the architects, just as it is incorrect to assert that Galileo's theory was the first theory ever formulated concerning the strength of materials.

3. Galileo's theory of the strength of materials

Although Galileo's First New Science initiated the decline of the doctrine of proportions of the Renaissance architects, as received from and further elaborated since Antiquity, especially from Vitruvius' De architectura, it has already been demonstrated that his theory is also rooted in practical knowledge and especially in the knowledge that was shared within the walls of the Venetian Arsenal.[25] The masters of the Venetian Arsenal and the way in which their knowledge and experience was coordinated and codified by its Commissioners could have made Galileo aware of the limits of applicability of what has been called here the doctrine of linear proportionality.

Galileo framed his theory using three models, one of which is the cantilever model (Figure 2). He tried to identify the resistance to fracture of a certain given prism of known dimensions and material, when the dimensions of the prism are hypothetically increased or decreased and when one extremity is fixed, for example driven into a wall, and a given weight suspended from the opposite extremity. Galileo moreover framed the cantilever model by considering the timber driven into the wall as a lever. Without entering into the details of Galileo's demonstrations, it is enough to know that he established a relation between the dimensions of the cantilever, including its thickness and its weight. According to this model, 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 weight alone. Galileo finally came to the conclusion that, if the length and the height of the cantilever driven into the wall are doubled, in order to maintain the same strength, its thickness must be tripled.

Disregarding the limits of Galileo's theory, three points are particularly relevant. First, Galileo's argument was a theory and not a doctrine because it is

[24] To prepare the Discorsi for printing in the Netherlands, Galileo organized a reading group in Venice around his friend Fulgenzio Micanzio. The military engineer Antoine de Ville belonged to this group and when he became aware of Galileo's theory, he wrote him a particularly aggressive letter. The relevance of this episode, considered as the symbol of Galileo's mining the fundaments of the doctrine of proportions of the architects, has been determined and described in M. Valleriani, Galileo Engineer (Springer, Dordrecht, forthcoming). See especially chapter IV. For further details, see also H. Vèrin, 'Galilée et Antoine de Ville. Un currier sur l'idée de matière', in Largo campo di filosofare, edited by J. Montesinos and C. Solis (Orotawa 2001), 307–21.

[25] Galileo's relation to the Venetian Arsenal is also discussed in section 8 of this work. For extensive work on Galileo's relation between his First New Science and the practical knowledge of the Venetian Arsenal, see J. Renn and M. Valleriani, 'Galileo and the Challenge of the Arsenal', Nuncius, 2 (2001), 482– 503 and M. Henninger-Voss, 'Comets and Cannonballs. Reading Technology in a Sixteenth-Century Library', in The Mindful Hands, edited by L. Roberts, S. Schaffer, and P. Dear (Amsterdam, 2007), 11–32.

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Figure 2. Galileo's cantilever model. From Galileo, Discorsi e dimostrationi matematiche intorno à due nuove scienze, attenenti alla Mecanica, & I Movimenti Locali (Bologna, 1655), 86. Permission: Library of the Max Planck Institute for the History of Science, Berlin.

formally structured and reduced to a principle, namely, the principle of the lever. The doctrine of proportions and the doctrine of linear proportionality concerned with the strength of materials were not in fact reduced to any theoretical principle but only to a building method that pivoted on the concept of modulus. Second, Galileo's definition of resistance to fracture makes uses of three independent parameters: the thickness, the length, and the weight, whereas the latter does not play any formal role in the doctrine of linear proportionality. Galileo's theory therefore is formally structured in a way that is able to treat all of these three parameters quantitatively (Figure 3). Third, Galileo was correct when he asserted that two objects, similar on the basis of the linear proportionality among their dimensions, have different strengths and, in particular, that the larger object is weaker. Generally speaking, the dimensions of the larger object must therefore be over proportioned in comparison with those of the smaller object in order to maintain the same resistance to fracture.

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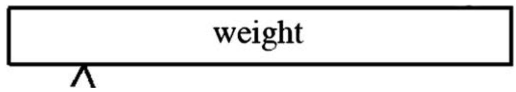

Figure 3. Representation of Galileo's three-parameter definition of the resistance to fracture.

Galileo was aware that his theory represented an attack on the generally accepted doctrine of linear proportionality:[26]

[. . .] even if the imperfections did not exist and matter were absolutely perfect, unalterable and free from all accidental variations, the mere fact that the larger machine is made by matter and exactly of the same material and in the same proportion as the smaller [machine], the large machine is identical to the smaller one in every respect except that it will not be as strong or as resistant to violent treatment; the larger the machine, the greater its weakness.

It is therefore irritating to historians of science that Galileo, although he possessed a copy of Andrea Palladio's treatise,[27] never quoted the Italian architects considered at the time to be the authorities on the doctrine of proportions. But the solution to this vexing problem may lie in the fact that Galileo did not need to quote the works of the architects because someone else had already done so. In the same way that Galileo told the reader at the beginning of the Discorsi that his First New Science was rooted in the practical knowledge of the masters of the Arsenal, he also identified the most advanced theory concerned with the strength of materials as being existent at the same time as he conceived his own. During the Second Day, Galileo lets Simplicio introduce Question XVI of Aristotle's Mechanical Questions. Simplicio compares Galileo's argument with the Aristotelian one:[28]

SIMP. You remind me now of a passage in Aristotle's Questions of Mechanics in which he tries to explain why it is that a wooden beam becomes weaker and can be more easily bent as it becomes longer, notwithstanding the fact that the shorter beam is thinner and the longer one thicker: and, if I remember correctly, he explains it in terms of the simple lever.

[26] The original text reads: '[. . .] astraendo tutte l'imperfezzioni della materia e supponendola perfettissima ed inalterabile e da ogni accidental mutazione esente, con tutto ciò il solo esser materiale fa che la machina maggiore, fabbricata del'istessa materia e con l'istesse proporzioni che la minore, in tutte l'altre condizioni risponderà con giusta simmetria alla minore, fuor che nella robustezza resistenza contro alle violente invasioni; ma quanto più sarà grande, tanto a proporzione sarà più debole'. From Galileo 1968 (footnote 8), 51 (author's italics).

[27] A. Favaro, La libreria di Galileo Galilei', Bullettino di bibliografia e di storia delle scienze matematiche e fisiche, 19 (1886), 1–77.

[28] The original text reads: 'SIMP. Ora mi fate sovvenire non so che, posto da Aristotele tra le sue Quistioni Mecaniche, mentre vuol render la ragione onde avvenga che i legni, quanto più son lunghi, tanto più son deboli e più si piegano, ben che i più corti sieno più sottili, e i lunghi più grossi; e se io ben mi ricordo, ne riduce la ragione alla semplice leva'. From Galileo 1968 (footnote 8), 164–65.

Salviati accepts Simplicio's challenge and appears to be well informed on the study of Aristotle's Mechanical Questions:[29]

SALV. Very true: but, since this solution seemed to leave room for doubt, monsignor Guevara, whose truly learned commentaries have greatly enriched and illuminated this work, indulges in additional clever speculations with the hope of thus overcoming all difficulties; nevertheless even he is confused as regards this particular point, namely, whether, when the length and thickness of these solid figures increase in the same ratio, their strength and resistance to fracture, as well as to bending, remain constant.

At the time of publication of the Discorsi, Guevara's commentary of 1627[30] was in fact the last one published after a long, intensive and successful series of commentaries written and published from the end of the fifteenth century.[31]
In the Discorsi Galileo did not only quote Guevera's commentary. In a note on the copy of the manuscript destined for Prague, which failed to be published, Galileo also quoted the commentary on the Mechanical Questions published by Giuseppe Biancani in 1615[32] in the same passage where he also quoted Guevara.[33] It is therefore Galileo who suggested the works of the Aristotelian commentators on the Mechanical Questions as a possible bridge between the doctrine of proportions of the architects and his own theory of the strength of materials.

4. Guevara's theory of the strength of materials
Aristotle's Mechanical Questions comprises a theoretical introduction and thirty-five arguments*the questions*which deal with very distinct problems of mechanical nature, most of which had practical origins. The aim of the work is to show how such a multiplicity of problems can be reduced and explained using one single principle, namely the principle of the lever. The lever is furthermore interpreted as performing a

[29] The original text reads: 'SALV. E verissimo: e perchè la soluzione non par che tolga interamente la ragion del dubitare, Monsig. di Guevara, il quale veramente con i suoi dottissimi comentarii ha altamente nobilitata e illustrata quell'opera, si estende con altre più acute specolazioni per sciorre tutte le difficoltà, restando però esso ancora perplesso in questo punto, se crescendosi con la medesima proporzione le lunghezze e le grossezze di tali solide figure, si deva mantenere l'istesso tenore nelle loro robustezze e resistenze nell'esser rotte ed anco nel piegarsi'. From Galileo 1968 (footnote 8), 164–65.

[30] G. di Guevara, In Aristotelis commentarii una cum additionibus quibusdam ad eandem materiam pertinentibus (Rome, 1627).

[31] Starting from the published version of corpus aristotelicum by Aldus Manutius in 1495–1498 and counting translations as well as commentaries and works that at least deal partially with some of the Aristotelian Questions, twenty works concerned with Aristotle's Mechanical Questions were written and mostly published before Giovanni de Guevara published his own commentary.

[32] J. Blancanus, Aristotelis loca mathematica: ex universis ipsius operibus collecta & explicita (Bononiae, 1615).

[33] The manuscript of the Discorsi was sent to Giovanni Pieroni, who was supposed to have the book printed in Prague far from the Roman censors. Pieroni never succeeded in accomplishing this task. The note concerned with Biancani's commentary is published in Galileo 1968 (footnote 8), 165, footnote no. 1. The copy of the manuscript sent to Pieroni is preserved at the Biblioteca Nazionale Centrale di Firenze, Banco Rari, A. 5.

circular motion in the same way as a balance.[34] Aristotle stated[35] the principle of the lever in the following terms: the greater the distance from the fulcrum, the easier the movement. Aristotle's Mechanical Questions is the first work to contain a formulation of the principle of the lever and at the same time still carries traces of the practical knowledge from which such a theoretical principle emerged.

Questions XIV and XVI deal with phenomena concerned with the strength of materials: Question XIV with the resistance to fracture and Question XVI with the bending phenomenon. They ask:[36]

(XIV) Why is a piece of wood of equal size more easily broken over the knee if one holds it with the hands at equal distance at the extremities, than if one holds it by the knee and quite close to it?

(XVI) Why are pieces of timber weaker the longer they are, and why do they bend more easily when raised; even if the short piece is for instance two cubits and light, while the long piece of a hundred cubits is thick?

Guevara's commentary on Question XVI is the one to which Galileo referred. Guevara's argument is particularly articulate and includes a general discussion of the constitution of matter.[37] Guevera conceived matter as being constituted of particles in such a way that if, for example, a cylinder placed horizontally bends, the particles constituting its lower part condense (constipatio/ condensatio), whereas those con-stituting the upper part rarefy (laxatio/rarefactio).

Guevara analysed comparatively the behaviour of a long lance or spear and of a short branch of weaker matter and, following his analysis of the behaviour of the particles in the upper and lower parts of the spear, he introduces implicitly the thickness of the spear as a fundamental parameter concerned with its strength. Discussing the behaviour of the branch, Guevara determined that (Figure 4):[38]

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

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[34] For an introduction to Aristotle's Mechanical Questions, see Damerow, Renn, Rieger, Weinig 2002 (footnote 3). See also Rose, Drake 1971 (footnote 2); F. de Gandt, 'Les mèchaniques attribuées a Aristote et le renouveau de la science de machines au XVI siécle', Les Etudes philosophiques, 3 (1986), 391–405 and Laird 1986 (footnote 2).

[35] Nowadays, the Mechanical Questions is mostly considered as a work written by Aristotle's pupils. Apart from Gerolamo Cardano, the attribution of the authorship to Aristotle was, however, universally accepted during the early modern period.

[36] Aristotle 1980 (footnote 1), 369 and 371.

[37] Antonio Becchi has shown that Guevara's general conception of the constitution of matter and of the behaviour of the timber was developed on the basis of the concept expressed by Bernardino Baldi in his commentary on the Mechanical Questions. For more details, see B. Baldi, In mechanica Aristotelis problemata exercitationes: adiecta succincta narratione de autoris vita et scriptis (Moguntiae, 1621) and A. Becchi, Q. XVI: Leonardo, Galileo e il caso Baldi, Magonza, 26 March 1621 (Venice, 2004).

[38] The original text reads: '[. . .] si brevitas ligni compensetur magna crassitiei, obstabit ex alio capite ipsamet eadem crassities propter maiorem multitudinem partium, quarum aliae constipari, aliae autem laxari debent cum fit ipsa inflexio'. From Guevera 1627 (footnote 30), 165.

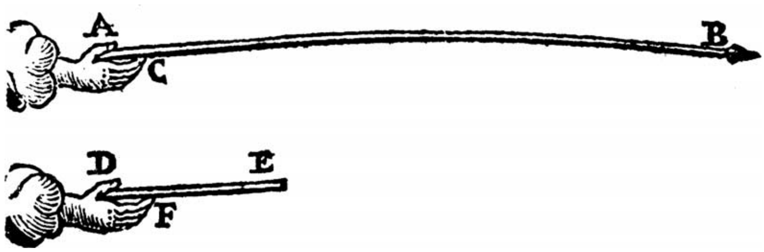

Figure 4. Guevara's comparison between a spear and a short branch held horizontally in one hand in the commentary on Aristotle's Question XVI. From Guevara 1627 (footnote 30), 164. Permission: Library of the Max Planck Institute for the History of Science, Berlin.

Following Aristotle, Guevera conceived of the spear and the branch as levers whose fulcrum is the place where they are held and which is close to one of the two ends of the object:[39]

He says that the greater bending of the longer timber takes place because, once the timber is placed in such a position, it is constituted similarly to a lever and a load, and having the fulcrum near the other extremity in the hand by which it is raised, the longer the part is, which is between the fulcrum and the other extremity, which represents the weight, the more necessary it is that it bends [. . .].

Guevara clearly applied the principle of the lever to explain the bending phenomenon of the spear and of the short branch in such a way that their lengths and thicknesses are considered as fundamental parameters for defining their strength. However, the same cannot be said for the weight because it is not considered to be an independent parameter. Although Guevara determined the weight to be the cause of the bending, this is conceived to be placed at the end-point of the object and thus the action of the weight is represented by the consequences of a longer or shorter distance between the fulcrum and the extremity. In other words, the weight is reduced to the length, and the length thus becomes the quantifiable parameter that causes the bending.

Once he had given the fundamental structure of his argument, Guevara proceeded to approach the comparison between two objects equal in every respect apart from their dimensions, which are linearly proportional to each other. According to the generally dominant concept, he took for granted and implicitly stated that such similar objects should have the same strength. However, Guevara, and not Galileo, was also the first to point to the fact that[40]

[39] The original text reads: 'Ait igitur ex hoc procedere maiorem inflexionem ligni procerioris, quod cum lignum ita suspensum, simul constituatur vectis, & onus, fulcimentum habens prope alterum extremum in manu à qua elevatur; quanto extensius fuerit id quod à fulcimento est versus alteram extremitatem, quae constituitor pondus; tanto magis ipsum inflecti necesse est [. . .]'. From Guevara 1627 (footnote 30), 163–64 (author's italics).

[40] The original text reads: 'Utrum verò servata eadem proportione crassitiei ad longitudinem, aequè facilè inclinetur magnum, ac paruum, seu longum, ac breve, non satis videtur constare'. From Guevera 1627 (footnote 30), 165.

If the same proportion of thickness to length is retained, one does not sufficiently see the correspondence that longer and shorter bend more or less equally easily.

From this point on in his argument, Guevara abandoned the attempt to deduce an explanation for such a lack of correspondence between the behaviour of two similar bodies. Instead, he continued to describe the observations he eventually accomplished:[41]

And thus, be that proportion a finger of thickness and a cubit of length to fifty fingers of thickness and fifty cubits: and finally a bar of iron or of wood with a thickness of one finger and with a length of one cubit will not bend so easily because of its weight, as a bar of wood or of iron with the thickness of fifty fingers and with a length of fifty cubits. [. . .]. Therefore, 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 that same sort of wood, and lead iron [. . .].

Guevara limited his argument to the description of vexing observations that Galileo at that time had already made at the Venetian Arsenal as well. The implicit definition of the strength of an object in his theory is a two-parameter definition* length and thickness, the weight being reduced to the length*namely the same definition of strength implicitly assumed by the architects' doctrine of linear proportionality (Figure 5).

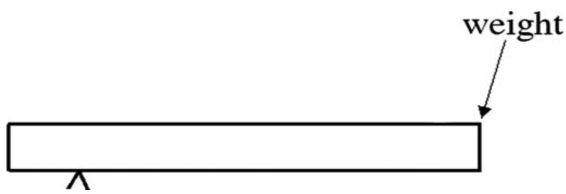

Figure 5. Representation of Guevara's two-parameter definition of resistance to fracture.

Being based on a theoretical principle, that is, the lever principle, Guevara's argument is therefore a theory that reformulated the architects' doctrine of linear proportionality within a deductive and theoretical frame. In other words, Guevara's theory is able to handle quantitatively the dimensions and thickness of the object for which the resistance to fracture has to be established. However, unlike Galileo's theory, it does not take into consideration weight as an independent parameter.

In Guevara's commentary, the doctrine of linear proportionality has become the 'theory of linear proportionality', though he had perceived its limits. This finally is the theory that Galileo critically referred to and that he intended to substitute with his own.

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[41] The original text reads: 'Eadem namque est proportio crassitiei unius digiti ad longitudinem unius cubiti atque quinquaginta digitorum ad quinquaginta cubitorum: & tamen vìrga ferrea, aut lignea si digitalis crassitiei fuerit longitudinisq. unius cubiti, non cum facilè suo pondere flectetur, ac lignum, vel ferrum quinquaginta digitorum crassitiei, totidemq. cubitorum longitudinis. [. . .] Ad haec proportio, quae auget facilitatem, aut difficultatem inflexionis in una specie ligni, non auget in alia sicut non aequè in ligno, ac ferro plumbo [. . .]'. From Guevara 1627 (footnote 30), 166.

5. Aristotle

During the Renaissance a commentary on an ancient work, such as Aristotle's Mechanical Questions, was not necessarily considered as something extraneous to the original work of the master. The commentary was mostly conceived as a work whose aim was to expand the arguments, describe the details, and evidence the assumptions. Certainly a commentary could contain criticisms and arguments that were intended to point out mistakes in the original text. But if these criticisms and mistakes were not explicit, an early modern commentary on an ancient work was generally considered to reflect the science of the ancient author. In other words, Guevara's theory tended to be considered as a theory of Aristotle.[42]

However, the original Aristotelian argument related to Question XVI does not correspond theoretically or structurally to the argument of Guevara's work that is related to the same question. The original Aristotelian text reads as follows:[43]

> 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 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? Because the first part, which the hand lifts, becomes like a fulcrum, and the other [part] at the end [becomes] like a weight. So that, the greater the distance from the fulcrum, the more it is necessarily being bent; because: the more it [the part] sticks out from the fulcrum, the more it is being bent. BNecessarily also the ends of the lever must be lifted up. > If the lever is then being bent, it is necessarily being bent more, while it is being lifted up. Precisely this happens with the longer pieces of wood; with the shorter ones, the exterior parts are close to the fulcrum at rest.

Aristotle clearly applied the principle of the lever and took the length of the piece of wood as the fundamental parameter for the application of the principle. The weight is considered to be placed at the end of the piece of wood most distant from the fulcrum so that it is reduced operatively to the length. The thickness, finally, appears in the argument in a qualitative way only. Although the thickness is clearly considered to be a factor capable of hindering the bending phenomenon, the argument does not contain a formal structure that could enable a comparison between two equal bodies whose dimensions, including the thickness, are proportional to each other in a quantitative way. Quantitatively, Aristotle's original

[42] For the role and the meaning of the commentary as a literary genre, see B. Gladigow, 'Der Kommentar als Hypothek des Textes', and W. Raible, 'Arten des Kommentierens*Arten der Sinnbildung*Arten des Verstehens', in Text und Kommentar, edited by Assmann, Jan and Burkhard (Munich, 1995), 35–73. See also I. Sluiter, 'Commentaries and the didactic tradition', and J.T. Vallance, Galen, 'Proclus and the non-submissive commentary', in Commentaries*Kommentare, edited by G.W. Most (Göttingen, 1999), 222–44 and 173–205. This point will be further discussed in section 7 of this work.

[43] Due to the crucial relevance of this passage from the Aristotelian text for the present argument, the original Greek text has been analysed and a new translation of Question XVI accomplished on the basis of various critical editions of the Greek text and mainly on Aristotele, MHXANIKA (Padova, 1982) edited by Maria Elisabetta Bottecchia. The translation, moreover, is one of the results of the workshop 'Q. XVI' held at the Max Planck Institute for the History of Science in Berlin on 24 August 2007. Participants were: Peter McLaughlin, Jörn Heinrich, Albert Presas I Puig, Klaus Corcilius, Matteo Valleriani. Finally, the translation has been further improved using the valuable advice given by one of the anonymous reviewers.

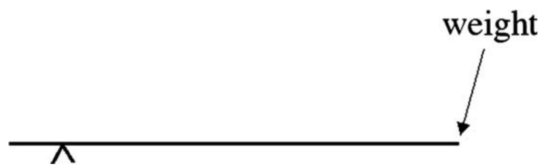

Figure 6. Representation of Aristotle’s one-parameter definition of resistance to fracture.

argument is able to treat the length only and therefore it is implicitly based on a one-parameter definition of the strength of an object (Figure 6).

A fundamental difference between Aristotle’s original argument and Guevera’s theory related to Question XVI has therefore been determined. Although evidently such a change is a consequence of a process of transformation of the Aristotelian argument, it is clear that Guevara could not formally deduce his theory from the original argument. Therefore, in order to frame such a transformation, a historical research is required, which is able to follow step by step the process of transformation of Aristotle’s Mechanical Questions.

6. The transformation of Aristotle’s Mechanical Questions: 1581 ‾1615

Giovanni di Guevara was not the first to formulate the theory of linear proportionality. In the following, each step of the process of transformation that was brought from the original Aristotelian argument to the theory of linear proportionality will be analysed. Since Guevara’s theory comes at the end of such a process of transformation, the use of reverse chronology will not only offer a more realistic picture of the historical research, but in particular help to understand the relevance of each step of the process by keeping the final result in mind.

Twelve years earlier in 1615 Giuseppe Biancani had published his Aristotelis loca mathematica,[44] part of which is dedicated to a commentary on the Mechanical Questions. Discussing Question XVI in a very concise way, Biancani first outlined the theoretical frame according to which an object placed horizontally and fixed at one end should be considered as a lever and, second, he reduced the weight to the length. Biancani’s commentary thus seems to comply with Aristotle’s original argument based on a one-parameter definition of strength. Surprisingly, however, he ended his textual commentary to Question XVI by approaching the doctrine of linear proportionality in its entirety and thus also the case of the comparison between two bodies constituted of the same material, one with larger proportional linear dimensions than the other (Figure 7):[45]

[. . .] 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,

[44] Blancanus 1615 (footnote 32).

[45] The original text reads: ‘[. . .] existimo, quod si maioris ligni longitudo ad eiusdem crassitiem haberet eandem proportionem, qua`m minoris longitudo ad eiusdem crassitiem, sicque vtrumque esset ab hypomoclio in eadem ratione diuisum, fore, vt vtrunque eodem modo inflecteretur, quia haberent pondera eandem rationem ad distantias ab hypomoclio [. . .]’. From Blancanus 1615 (footnote 32), 177.

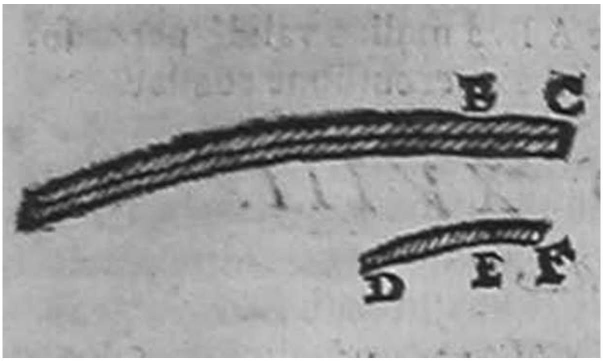

Figure 7. Biancani's comparison between two similar objects held horizontally in one hand in the commentary to Aristotle's Question XVI. From Blancanus 1615 (footnote 32), 177. Permission: Library of the Max Planck Institute for the History of Science, Berlin.

> they would then bend in the same way, since the weights would have the same relation to the distances to the fulcrum [. . .].

Clearly Biancani assumed a two-parameter definition of resistance to fracture, as did Guevara in his theory and the architects in their doctrine. Thus, in this one aspect Biancani's and Guevara's theories do not differ from each other. They do differ, however, in the way the thickness is included in the argument as a fundamental parameter. Whereas Guevara established it as a consequence of his conception about the constitution of matter and its analysis of the behaviour of objects whilst bending, Biancani simply added this argument to the original Aristotelian one and stated its formal deducibility from the latter. As shown earlier, however, from Aristotle's argument, based on a one-parameter definition of resistance to fracture, no theory of linear proportionality can be deduced as this is based on a two-parameter definition.

Tracing back the chronological line of transmission of Aristotle's Mechanical Questions two works can be identified that filled this theoretical gap. The first is Bernardino Baldi's In mechanica Aristotelis problemata exercitationes[46] which he began to write in 1581.[47] This was published posthumously in 1621. The second is Giovanni de Benedetti's Diversarum speculationum mathematicarum, et physicarum liber,[48] pub-lished in 1585, which deals partly with the Mechanical Questions as well.

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[46] Baldi 1621 (footnote 36).

[47] It is generally acknowledged that Baldi's commentary on Aristotle's Mechanical Questions was written between 1581 and 1582. As Antonio Becchi has shown this date corresponds to the year Baldi started work on this issue. Although some details of the circulation of Baldi's manuscript are known, and although it is known that he worked on his commentary in several phases, it remains uncertain when exactly the manuscript took on the form in which it was finally published posthumously in 1621. For more details, see Becchi 2004 (footnote 37), 57 62.

[48] G.B. d. Benedetti, Diversarum speculationum mathematicarum et physicarum liber (Turin, 1585).

This text was published on page 199 of the article "The Transformation of Aristotle's Mechanical Questions".

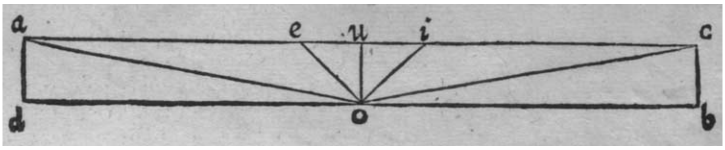

Figure 8. Benedetti's argument for the resistance to fracture of a timber. From Benedetti 1585 (footnote 47), 161. Permission: Library of the Max Planck Institute for the History of Science, Berlin.

Benedetti commented on Aristotle's Question XIV and therefore directly discussed the issue of resistance to fracture. The model he introduced corresponds partially to the theory of linear proportionality (Figure 8):[49]

Imagine straight lines drawn from point O to points A, E, I, and C [. . .] points E and I of the two lines EO and IO in the middle exert more effort at the center O, than the points A and C of the two lines AO and CO which is beneficial; therefore they will have more force also at points A and C than at E and I.

Benedetti tried to explain geometrically why a timber is easier to break if it is held at its two extremities and the knee is placed at its centre than if the timber is held at two equidistant points closer to the centre. His demonstration, which is based on the principle of the lever, clearly considers the thickness of the timber as an independent parameter so that it can be said that his implicit definition of resistance to fracture is a two-parameter definition as well.
Benedetti's argument, however, allows a comparison between two timbers of different length but whose thickness remains the same. Since the theory of linear proportionality allows a comparison between two timbers of different length and thickness, though their ratios are proportional to each other, Benedetti's argument can be identified only partially with such a theory and as a less powerful argument.
Three years before Benedetti's publication, Baldi had started writing his commentary on Aristotle's Mechanical Questions. Baldi's extremely long and elaborate commentary on Question XVI has recently been analysed and identified as a milestone for the history of architecture: Baldi applied his considerations on the strength of materials to several fundamental issues of the architects' doctrine of construction from the end of the sixteenth century, for example, to the doctrine of construction of arches and vaults.[50]

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[49] The original text reads: 'Imaginemur lineas rectas ductas a puncto .o. ad loca .a.e.i. et .c. [. . .] loca .e.i. mediantibus duabus lineis .e.o. et .i.o. magis annitentur .o. centro, quàm loca .a. et .c. duarum linearum .a.o. et .c.o. beneficio, unde vim quoque maiorem habebunt in .a. et .c. quàm in .e. et .i'. From Benedetti 1585 (footnote 48), 161.

[50] The following analysis of Baldi's work is deeply indebted to the research of Antonio Becchi. For more details, see Becchi 2004 (footnote 37).

This text was published on page 200 of the article "The Transformation of Aristotle's Mechanical Questions".

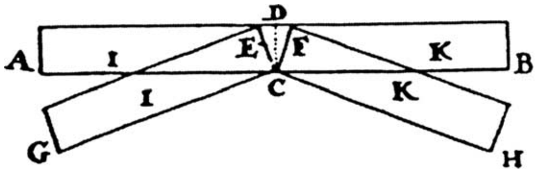

Figure 9. Baldi's argument for the resistance to fracture of a timber. From Mögling 1629 (footnote 50).

Baldi's commentary on Question XVI is based on his concise analysis of the resistance to fracture of a timber presented in the commentary on Question XIV. Baldi's argument is similar to Benedetti's (Figure 9):[51]

Therefore [. . .] if the line CD is drawn perpendicular to AB, let the long piece of wood be AB, and C its central point, and if the knee is moved to point C and the hands are opened as far as points A and B. Pushing on both sides, the piece of wood will not break as long as the two parts joined at CD do not separate, moving one to E and the other to F. [If they do this], then the piece of wood will break and, while the center C remains immobile, the two parts, forming the angle GCH, move to GC and HC. If the piece of wood is now brought back to its former state and, again directing the knee to C, the hands are moved as far as points I and K which are closer than A and B to the center C. It is now more difficult to cause the fracture. We see two levers in the original piece of wood, ACD and BCD, whose extremities are joined at the fulcrum C, common to both of them. These are levers placed at an angle like those we examined in Question V. In this case the resistance is not constituted by a weight but by the point D, at which the two parts are joined. This is the resistance that must be superseded so that the fracture can occur. And this happens more easily if the forces [potentia] are exerted at the most distant points A and B than at the points I and K, closer to the point C. In fact the resistance D is to the force [potentia] exerted at A as AC to CD and the resistance D to the force [potentia]

[51] The original text reads: 'Esto igitur [. . .] lignum oblungum AB, cuius medium C, linea ducatur CD perpendicularis ipsi AB. Admoueatur genu puncto C, manus verò diuaricentur in AB, facta igitur vtrinque impressione, lignum non frangetur, nisi partium in CD coniunctarum separatio fiat, sit queue altera in E, altera verò in F, fractum ergo erit lignum, & centro C immobili permanente, partes facto angulo GCH erunt in GC, HC: Modò lignum suae integritati restituetur, & denuò admoto genu puncto C, manus diducantur in I, K, quae loca viciniora sint ipsi C, quam AB, Dico hinc difficilius fractionem fieri quam ex AB. Consideramus enim in integro ligno AB, duos vectes ACD, BCD, quorum anguli concurrunt in commune fulcimentum C, Sunt autem vectes angulati, & eius naturae, quam examinauimus in quaestione 5. Est igitur resistentia, qua ligni partes vniuntur in D, loco ponderis: superanda haec est, vt ligni fiat fractio. Dico id facilius cessurum, si fiat ex punctis A, B, remotioribus quam ex IK, ipsi puncto C propioribus: et enim vt AC, ad CD, ita resistentia quae fit in D ad potentiam in A, item vt se habet IC ad CD, ita resistentia in D ad potentiam in I, sed minor est proportio IC ad CD, quam AC ad CD. ergo facilius potentia quae est in A, resistentiam superabit, quae est in D, quam ea quae est in I, quod fuerat demonstrandum'. Figure 9 is not the original illustration from Baldi's work, as this shows a great number of mistakes made by the editor concerning its illustrations made by the editor. Following Antonio Becchi, the illustration from D. Mögling, Mechanischer Kunst-Kammer Erster Theil (Frankfurt, 1629) is used here. In his work Daniel Mögling also commented Baldi's commentary on Question XVI. For more details, see also Becchi 2004 (footnote 37), 168.

exerted in I as IC to CD, but the ratio of IC to CD is smaller than the ratio of AC to CD. Therefore the force [potentia] exerted at A overcomes the resistance at D more easily than the force [potentia] exerted at I, as one had to demonstrate.

Baldi applied the principle of the lever and assumed a two-parameter definition of resistance, as in the case of Benedetti.[52] In the same way, Baldi's argument can be read to allow the comparison between two timbers of different length but with the same thickness. Neither model is able to quantify how the force must increase when the hands are placed closer to the centre of the timber. This point is in fact treated only qualitatively. But Baldi's model is particularly relevant for two other reasons. First, because it is probably the first commentary on the Mechanical Questions that contains a two-parameter definition of resistance to fracture[53] and, second, because it allows an inference about where such a definition originated.

Baldi asserted in his commentary on Question XVI that he wanted to discuss the implications of his demonstration of the argument for Question XIV in reference to some relevant aspects of the architects' doctrine of construction in order to render the Mechanical Questions useful to them. In other words, Baldi readdressed the function of Aristotle's work to enhance the work of the architects. Since, moreover, he had also been active as an architect, he possessed the background necessary to fundamentally change the definition of resistance to fracture from the one-parameter, original of Aristotle's argument, to the two-parameter definition as taken from the architects' doctrine of proportions.[54]

In his work Bernardino Baldi first introduced the two-parameter definition into the arguments of Aristotle's Mechanical Questions and gave a method for comparing two timbers of different lengths but of the same thickness using, however, Aristotle's fundamental idea to apply the lever principle to explain the phenomena of breaking and bending. In 1585, Benedetti did the same in reference to the phenomenon of breaking and formulated a demonstration more geometrico which eventually helped to further identify Benedetti's argument as the part of the architects' doctrine of proportions that deals with the same topic, namely, the doctrine of linear proportionality. This was finally extrapolated in 1615 by Giuseppe Biancani, who dealt with it in the frame of the argument for Question XVI; Biancani suggested comparing on the basis of the lever principle two timbers of different lengths and thicknesses which are linearly proportional to each other. Finally, in 1627 Giovanni di Guevara attempted to provide an extensive theoretical formulation of the theory of linear proportionality and observed at the same time its limits of applicability.

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[52] In the case studies discussed by Baldi in his argument for Question XIV, he clearly applied the principle of the angular lever, anticipating in this way aspects of an eighteenth-century theoretical approach to a beam's resistance to fracture. For more details, see Becchi 2004 (footnote 37), 77.

[53] Baldi's commentary was first published in 1621. Since his argument is based on a concept according to which matter is constituted of particles and the bending behaviour is analysed in these terms, as mentioned earlier it is easy to infer that Guevara's entire argument, published in 1627, was deeply influenced by Baldi's work. Concerning the works of Benedetti and Biancani, however, it is not possible to establish the degree to which their works were indebted to Baldi's.

[54] For Baldi's architectural activities, see A. Serrai, Bernardino Baldi: la vita, le opere, la biblioteca (Milan, 2002), 23–24, in particular footnote no. 24.

7. The impact of and the reasons for the transformation of the Mechanical Questions The theory of linear proportionality as a result of the transformation process of the Mechanical Questions had a profound impact which has not yet been evaluated. It has been shown that this theory, and not the architects' doctrine of proportions, is the one Galileo referred to and was willing to criticize and substitute. But it was not only engineer-scientists[55] such as Galileo who considered this theory. As mentioned earlier, the arguments developed by the commentators on the ancient works, in this case by the commentators on Aristotle's Mechanical Questions, were mostly considered by the contemporary reader to be original arguments of the original author. The best demonstration of this point, which at the same time shows the great scientific impact of the theory of linear proportionality, is given by the treatises written by architects and machine-builders after Biancani's and Guevera's publica-tions. In his Le Machine, published in 1629, Giovanni Branca for example approached this issue on the first page of the chapter dedicated to the reader:[56]

[. . .] these present figures, concerned with water, as well as with animal operations, and pneumatics [. . .] contain all those principles that Aristotle discusses and suggests in his Mechanics [. . .]. No one should lose hope, while trying to build some of these machines, if the desired effect is not produced; [. . .], sometimes wonders are made in miniature and then, when enlarged, the structure is lost, but one should not be surprised because the problem does not come from the Mechanics and its principles, but from the [machine] builder [. . .].

Giovanni Branca was a machine-builder and, according to Vitruvius and to the Italian Renaissance architects, the same fundamental rules valid for the construction of buildings are also valid for the art of building machines.[57] Branca's foreword to the reader approaches the case when a builder begins work by designing and creating a model of a machine and then builds the real size machine in linear proportion to the measurements of the models. Although Giovanni Branca can be considered as an architect and engineer, he did not quote this rule as a Vitruvian rule of the doctrine of proportions but as a principle of Aristotle's Mechanics. He did so because of the works of Bernardino Baldi, Giovanni de Benedetti, Giuseppe Biancani and Giovanni de Guevara, written during a time period of only 45 years.
In his To the reader Branca offered advice rather than an introduction. He mentioned the possibility that while building to scale and, specifically, in the transition from the model to the real size object, it could turn out that the real size machine or building would not function properly or would not be stable or resistant. It has already been said that the doctrine as well as the theory of linear

[55] For the definition of the early modern engineer-scientist, especially Galileo, see Renn 2001 (footnote 6); Renn, Valleriani 2001 (footnote 25); M. Valleriani, 'A View on Galileo's Ricordi Autografi', in Largo campo di filosofare, edited by J. Montesinos and C. Solìs (Orotawa 2001), 281–92; and M. Valleriani, 'Galileo in the Role of the Caster's Assistant: The 1634 Bell of the Torre del Mangia in Siena', Galilaeana, V (2008), 89–112.

[56] The original text reads: '[. . .] queste presenti figure, tanto di acqua, quanto di animale operatione, et spiritali [. . .] nelle quali vi son dentro tutti quelli principij, che Aristotile tratta, & propone nelle sue Mechaniche [. . .]. Ne deve alcuno smarrirsi, mentre ponerà in opera alcune di queste machine, se non gli riuscisse l'atione desiderata; [. . .], che alle volte in picciola forma si opron quasi miracoli, che in forma grande, alcune volte si perde la scherma, e però non è da maravigliarsi, perche il diffetto non procede dalle Mecaniche, ne da suoi principij, ma solo dall'operante [. . .]'. From the reprint G. Branca, Le machine (Turin, 1977), Al lettore, first page.

[57] Vitruvius discussed the art of building machines in Book X of his De architectura.

proportionality were erroneous. Consequently, failures in buildings and machines were common. Many practitioners, architects, engineers, and machine-builders complained about this situation, even Vitruvius:[58]

For not everything can be carried out according to the same principles. There are some things that achieve large-scale results like those achieved with small models. And then there are other things for which models cannot be made at all, and they must be built to scale in the first place. And some things that seem perfectly realistic in a model vanish when their scale begins to be enlarged [. . .].

During the Renaissance the complaints multiplied. In his De divina proportione, completed in 1498 and first published in 1509, Luca Pacioli, in a rhetorical manner, complained that:[59]

Even the tailor and the shoemaker use geometry and do not know what it is; and so the masons, the carpenters and the smiths and all the practitioners use measure and proportion and do not know why, as it has been said at other times, everything consists of number, weight and measure: But what can we say about the modern buildings, commissioned and disposed according to their order by means of various and different models whose results are pleasant to the eye because they are small, and then, in real size, since they do not support the weight, not only do they not reach a thousand years, but they collapse before the third year has ended?In his Tre Discorsi sul modo d'alzare le acque, published in 1567, the same year in which Daniele Barbaro published his famous commentary on Vitruvius, Giuseppe Ceredi warned that:[60]

[. . .] in almost all of the small models the effects of similar operations turn out very well, & in the real work then defraud the authors [. . .].

While describing the work of the mechanician, that is, of the one who actually built machines, Bonaiuto Lorini stated in his Delle fortificationi, published in 1597,[61] that:

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58 Vitruvius, Rowland, Howe, Dewar 1999 (footnote 11), XVI, 5.

59 The original text reads: 'Ancora el sarto e calzolaro usano la geometria e non sanno che cosa sia; e sì murari, legnaoli, fabbri e ogni artefici usano la mesura e la proportione e non sanno, peroché commo altre volte è detto, tutto consiste nel numero, peso et mesura: Ma che diremo de li moderni edifizii, in suo genere ordinati e disposti con varii e diversi modelli quali a l'occhio per che alquanto rendino vaghezza per lor esser piccoli, e poi nelle fabriche non regano al peso e, non che a mill'anni arivano, 'nanze al terzo ruinano?' From L. Pacioli, Divina proportione: opera a tutti glingegni perspicaci e curiosi necessaria ove ciascun studioso di philosophia, prospectiva pictura, sculptura, architectura, musica, e altre mathematice, suavissima sottile e admirabile doctrina consequira: e delectarassi co varie questione de secretissima scientia (Venice, 1509). The text used here is from Di Pasquale 1996 (footnote 8), 83.

60 The original text reads: '[. . .] in quasi tutti li modelli piccioli gli effetti di simili operationi rieschino benissimo, & in opera reale poi facciano restare ingannati i loro autori [. . .]'. From G. Ceredi, Tre discorsi sopra il modo d'alzar acque da'lvoghi bassi: Per adacquar terreni. Per leuar l'acque sorgenti, & piouute dalle ca[m]pagne, che non possono naturalmente dare loro il decorso. Per mandare l'acqua da bere alle Città, che n'hanno bisogno, & per altri simili vsi; Opera non piu stampata (Parma, 1567), 48.

61 This work makes use of the 1609 edition of Lorini's Delle fortificationi. The original text reads: '[. . .] fabricare le proposte machine, e quelle sapere proporzionatamente 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 necessarij suoi fondamenti'. From B. Lorini, Delle fortificationi (Venice, 1609), 196.

[. . .] build the proposed machines, and to know not only how to proportionally assemble and rule them, but, with the clarity that one wants, 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 by the force of it, as often happens to those who only trust the ease showed by the small Models, without knowing its necessary grounds.

Apart from Pacioli's testimony, the main problem seems to be the model: this was the architects' fundamental instrument for executing the design and then the construction of a building or of a machine.[62] This was the case in Vitruvius's time as well as during the Renaissance. If the machine or the building represented a new design, first a model was created and then the real size object was built to scale.

It is therefore difficult to understand why an erroneous doctrine of proportions was established in the first place, and then adhered to for such a long time, even though problems in applying this doctrine were already known in Antiquity. In his book, Salvatore di Pasquale is able to argue convincingly that, in Vitruvius's time, the limits of the doctrine of proportions were not exposed as often as they were during the early modern period. The employment of different materials, especially strong bonding mortar, and moreover a building concept based more on the issue of stability than of resistance, could explain why such a doctrine was developed and established in Antiquity. In other words, the doctrine of proportions was satisfactory at that time at least as far as the construction of buildings was concerned, that is, as long as resistance to fracture and deformation of materials remained secondary issues.[63] Due to the changes in architectural styles, in building materials and in all other issues relevant for architectural enterprises such as organization and training etc., the limits of the doctrine became more evident during the early modern period. Di Pasquale claims that this situation is mirrored by the fact that the Italian architects who received, further elaborated and transmitted the Vitruvian doctrine of proportions constantly added individual solutions, according to the great experience accumulated during the Renaissance, to all the possible problems related to resistance to fracture of determined architectural elements. In practice, once the doctrine of proportions had been accepted, the work of the architects was based on their expertise and skill in recognizing and finding ad hoc solutions to fill the gap between theory and praxis. Finally, the failures were considered to be caused mostly by the irregularities of matter.

Although Di Pasquale's argument may be able to explain how the doctrine of proportions could survive for such a long time, it does not help to understand why those aspects of the doctrine related to the strength of materials were shared by the commentators on Aristotle's Mechanical Questions in a way that transformed them into a theory. Although Vitruvius as well as the Renaissance architects did not fundamentally differentiate the art of building from the art of constructing machines and so considered their rules valid for both activities, it might be helpful to consider them distinctly in order to formulate a hypothesis for the reasons for such an

62 For the epistemic meaning of the model in the frame of practical knowledge, see M. Popplow, 'Presenting and Experimenting. Renaissance engineers' employment of models of machines', in: Les machines à la Renaissance, edited by P. Brioist, L. Dolza and H. Vérin (in preparation).

63 For more details, see Di Pasquale 1996 (footnote 8), 90–106.

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intensive and profound transformation of some of the Aristotelian arguments by merging them with an erroneous doctrine of linear proportionality.

Both arts used the model as a fundamental instrument to design and conceive the object to be built. Models for buildings, however, were fundamentally different from models for machines. Whereas models for machines did not differ structurally from the real size machines, models for buildings could not be compared as easily to the real size building because, for example, they were not made of the same materials. The models of machines were made of wood, just like the actual machines. From this difference it can be inferred that, while passing from model to real size, the doctrine of proportions was applied more accurately with the building of a machine and therefore the collapse of real size machines were probably particularly frequent. According to the testimonies at our disposal this seems in fact to be the case. Vitruvius, for example, also made clear the limits of the theory of proportions concerning the firmitas at the end of his work, in the tenth book which deals with building machines. Giuseppe Ceredi, Bonaiuto Lorini and Giovanni Branca did the same. Galileo, though he did not criticize the doctrine of proportions but the theory of linear proportionality, took naval architecture into consideration which also dealt with wooden constructions. It was therefore the machine-builder who mostly experienced failure when applying first the doctrine and later the theory of linear proportionality.

The writing activities of the machine-builders increased enormously during the sixteenth century. Moreover, according to Mario Biagioli, the social status of practitioners active within the frame of the military arts significantly improved and machine-makers were often employed for military reasons. This was not because of a need for new catapults or other wooden weapons, which were about to become obsolete, but because of the urgent need for light and fast machines for use in the defense of fortresses, for example, machines to lift cannons on to wagons. In Lorini's time, preparations to defend a fortress could take up to a week and personnel were specially trained to accomplish this task. All architectural enterprises, arsenals and harbors, which were constantly increasing in number and dimension during the Renaissance, required a great number of efficient machines, mostly to lift weights quickly in a number of different contexts. Therefore, a hypothesis can be formulated that the increasing relevance of machine building in the sixteenth century drew attention to the significance of building methods, especially as the collapse of real size and new machines was happening too often to be economically and militarily sustainable. The doctrine of linear proportionality, that is, those aspects of the architects' doctrine of proportions concerned with the strength of materials must have been commonly discussed towards the end of the sixteenth century. Bernardino Baldi began the process of transformation on the basis of a kind of merging of two roles into one; he was both a commentator and worked as an architect. But Baldi's work was first published in 1621, and what is known about the earlier circulation of his manuscript is not enough to show unequivocally whether his work influenced those of Benedetti and Biancani.[64] Giovanni Benedetti and Giuseppe Biancani were certainly not architects, but both had approached this issue in such a way that within

[64] Whereas Giovanni di Guevara was certainly aware of Baldi's work*he mentioned it directly in his commentary*a direct connection between Baldi's and Galileo's works has not been demonstrated, apart from the fact that Galileo was certainly familiar with Guevera's commentary. See also footnote no. 47.

a few years the theory of linear proportionality was fully formulated. They were not yet aware that the theory was wrong and thus their attempts to found this theory on the lever principle and so elaborate a formal deductive theory was probably the best method they had at their disposal to clarify and check the validity of the building methods of the architects and machine-builders, though the commentators obviously did not necessarily have this aim consciously in mind. But once he had the theory at his disposal, Galileo was able to accomplish his analysis and so suggest a new theory based on a new definition of resistance to fracture.

8. Transformation: from Aristotle to Galileo

Aristotle's original text emerged from an attempt to furnish a theoretical fundament*an explanatory model*to a series of results and applications of practical knowledge. In other words, Aristotle's Mechanical Questions is the output of a process of theoretization of practical knowledge. Concerning the strength of materials, Aristotle's theory was based on a one-parameter definition of resistance to fracture of an object, namely its length (Figure 10).

Between the end of the sixteenth- and the beginning of the seventeenth century, in the frames of architecture and the art of machine building, practical knowledge concerned with the strength of materials was more advanced in comparison with the theoretical developments at disposal at that time, when it was still represented by the original Aristotelian theory. The doctrine of linear proportionality was based on a two-parameter definition of resistance to fracture of an object. These were the thickness and the length. The increasing relevance of the work of such practitioners, on the one hand, and the increasing pressure on machine builders because of their

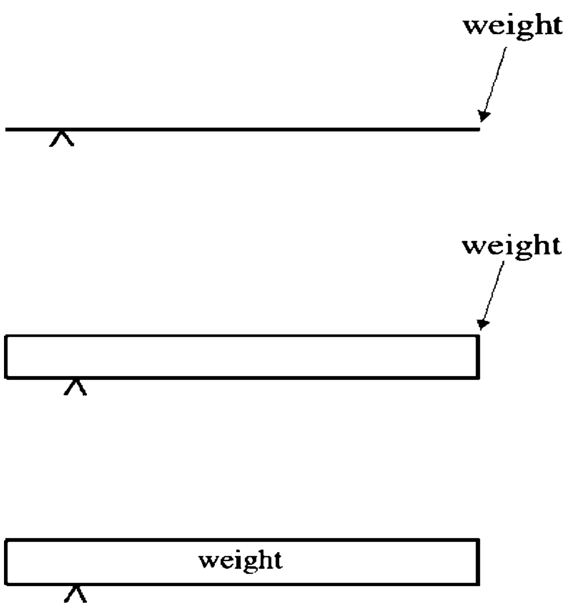

Figure 10. From top to bottom: Aristotle's original one-parameter definition of resistance to fracture; early modern Aristotelian two-parameter definition of resistance to fracture; Galileo's three-parameter definition of resistance to fracture.

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frequent failures, on the other, caused a transformation of Aristotle's argument that led to the formulation of a theory of linear proportionality based on the same definition of resistance to fracture of the doctrine of the practitioners. This allowed commentators such as Giovanni di Guevara to begin investigations into the causes of the machine-builders' failures and, less frequently, those of the architects.

Because of his opportune involvement in an official enquiry of the Collegio della Milizia da Mar of Venice,[65] Galileo was able to observe and share the practical knowledge concerned with the strength of materials probably in the most advanced state reached by practitioners during the Renaissance. Basing his research on the knowledge shared at the Arsenal, Galileo was finally able to approach Guevara's theory critically and to formulate a successive theoretical step, namely a theory of the strength of materials based on a three-parameter definition: the thickness, the length and the weight. Due to the integration of the knowledge and experience of the architects and machine-builders into the arguments of the Mechanical Questions, Galileo was finally able to formulate a theory which was not only a reaction to Guevara's theory but also a theory which gave a new explanatory model to frame the reasons for the frequent failures experienced by practitioners.

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[65] For more details, see Renn, Valleriani 2001 (footnote 25).