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THE INDIVIDUAL LIMIT OF NATURAL
SUBSTANCES: ARISTOTLE AND GALILEO ON THE
STRENGTH OF MATERIALS

ABSTRACT: The Aristotelian text known as *Quaestiones mechanicae* had an extensive and explicit influence on Galileo's *Discourses and Mathematical Demonstrations Relating to Two New Sciences* (1638). In particular, one of the thirty-five questions posed and solved in *Quaestiones mechanicae*, is the problem discussed under the title "Problem of the breaking strength of materials" (Problem XVI). It is discussed and solved by Galileo in a manner very different from the way in which, at the time of its formulation, Aristotle treated it. This article analyses the two authors' treatments, comparing the proposed solutions, also in the light of both scientific and philosophical positions. The following analysis addresses first of all the exposition of the problem put forth by Galileo, and then looks at the solution he proposed. After this, Galileo's proposal is compared to Aristotle's, in order to clarify the notion of 'individual limit', which appears in this paper's title.

RÉSUMÉ: Le texte d'Aristote des *Quaestiones mechanicae* a certainement influencé les *Discours et démonstrations mathématiques concernant deux sciences nouvelles* de Galilée (1638). En particulier, l'une des trente-cinq questions posées et résolues par son auteur est le problème de la résistance des matériaux (Problème XVI). Il fut traité et résolu par Galilée d'une façon très différente de celle d'Aristote. L'auteur de cet article a comparé les deux solutions, à la lumière des perspectives philosophiques d'Aristote et de Galilée. Il analyse d'abord l'exposition du problème telle qu'elle est faite par Galilée, compare ensuite la solution de Galilée à celle d'Aristote et, enfin, prend en compte un certain nombre de passages de diverses œuvres d'Aristote, afin d'instituer une comparaison entre les deux philosophes pour ce qui est de leur conception de la limite individuelle de chaque substance, conception déterminante pour le sujet traité.

KEYWORDS: Aristotle; Galileo; Strength of materials; Individual limit; *Quaestiones mechanicae*; Fragility; *antarkēia*; *gagliardia*; *Translatio studiorum*

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ARTICLES

The Problem of the Strength of Materials

An interesting case of *translatio studiorum* is represented by the work known as *Mechanica* or *Quaestiones mechanicae*, as it was reprised in a crucial moment by modern science.¹ In fact, it is well known that in the 17th century a particular form of *translatio studiorum*, which was both philosophic and scientific, came about. It was at that time that Galileo was inspired by the *Quaestiones mechanicae* when elaborating his scientific beliefs, and constantly compared his beliefs to those of Aristotle. The *Quaestiones mechanicae*, in antiquity believed to be written by Aristotle, experienced a completely different fate from the other works included in the *Corpus Aristotelicum*.² At the end of the 15th century, Aldo Manuzio's typography published the first Greek printed edition,³ which circulated widely throughout the 16th and the first half of the 17th century. At that time, it was considered to be the first treatise on mechanics in history and represented the entire body of mechanical science.⁴ In the 19th

¹ Aristotelis *Opera* ex recensione I. Bekkeri edidit Accademia Regia Borussica, 2, Berolini, Reimer, 1831.

² For more information on this subject, see the article P.L. Rose and S. Drake, "The Pseudo-Aristotelian *Questions of Mechanics* in Renaissance Culture", *Studies in the Renaissance*, 18, 1971, p. 65-104, as well as the more recent studies by L. Olivieri, *Certezza e gerarchia del sapere. Crisi dell'idea di scientificità nell'aristolismo del secolo XVI*, Padova, Antenore, 1983; G. Micheli, *Le origini del concetto di macchina*, Firenze, Olschki, 1995; M. Camerota – M.O. Helbing, *All'alba della scienza galileiana. Michel Varro e il suo "De motu tractatus"*, Cagliari, Cucc, 2000; M. E. Bottecchia Dehò, *Galileo. Lettore dei "Mechanica"*, Soveria Mannelli, Rubbettino, 2007. Regarding the philosophic conceptualization behind the work, see C. Rossitto, "Concetto e ruolo dell'opposizione nei *Mechanica* aristotelici", in E. De Bellis (ed.), *Aristotle and the Aristotelian Tradition*, Soveria Mannelli, Rubbettino, 2008, p. 343-368.

³ Between 1495 and 1498, after having been more or less ignored throughout the Middle Ages. For the reception of the *Quaestiones mechanicae*, see M.E. Bottecchia Dehò, *Introduzione a Aristotele, Problemi meccanici*, a cura di M.E. Bottecchia Dehò, Soveria Mannelli, Rubbettino, 2000, p. 11-16.

⁴ The Latin translation of the work, completed in 1525 by Nicolò Leonico Tomeo, should be mentioned, as well as the paraphrase by Alessandro Piccolomini (1547) and the commentaries by Henri de Monantheuil (1599) and Francesco Maurolico (1613). The 16th and 17th century scholars of mechanics put most of the problems discussed in the work to test. Some of these scholars were in Niccolò Tartaglia (*Quesiti et invenzioni diverse*) and Girolamo Cardano (*De subtilitate*). Finally, it should be kept in mind that the work was analysed also by the great philosophers and scientists of the early 1600s. In particular, Johannes Kepler in *Astronomiae pars optica*

century however, the authenticity of the work was put into question, causing it to be excluded from 20th-century translations of Aristotle's works.⁵ The exclusion of *Quaestiones mechanicae* has resulted in an underestimation of the role it played in works by someone as important as Galileo Galilei,⁶ despite the fact that Galileo mentions the treatise several times.⁷

(1604) investigates the second problem of the *Quaestiones mechanicae*, while Francis Bacon analyses the treatise in *De augmentis scientiarum* without ever doubting its authenticity.

⁵ It is useful to conduct some considerations on the debate concerning the genuineness of the work, which took place in modern and contemporary times. During the XIX century many philosophers, philologists and historians of the science spoke about this argument: Valentin Rose supported the non-genuineness of the work (V. Rose, *De Aristotelis librorum ordine et auctoritate commentatio*, Berolini, Reimer, 1854, p. 190; 192), like Alfred Gercke did at the end of the century (A. Gercke, *Aristoteles*, in RE II 1, Stuttgart, 1895, col. 1044). During the XX century, Johan Ludvig Heiberg and Tomas Heath, having detected some inconsistencies in the use of some terms, rejected Aristotle's authorship of the work, stating though that the same must have been of Aristotelian School (J.L. Heiberg, "Mathematisches zu Aristoteles", *Abhandlungen zur Geschichte der mathematischen Wissenschaften mit Einschluss ihrer Anwendungen*, 18, 1904, p. 3-49, p. 29; T. Heath, *Mathematics in Aristotle*, Bristol, 1998, Oxford, 1949¹, p. 227). Recently, scholars like Fritz Krafft and Helmuth Schneider opted for the genuineness of the work (F. Krafft, "Dynamische und statische Betrachtungsweise in der antiken Mechanik", Wiesbaden, Boetius X, Wiesbaden, 1970, p. 81; H. Schneider, *Das griechische Technikverständnis von den Epen Homers bis zu den Anfängen der technologischen Fachliteratur*, Darmstadt, Wissen, 1989, p. 234), while Maria Elisabetta Bottecchia Dehò stated that: "Si rimuovono così gli ostacoli ad esprimere per i *Mechanica* – come sembra derivare dalle ipotesi meglio argomentate – ipotesi di opera genina, nel senso però di opera nata ed elaborata nella scuola" (M.E. Bottecchia Dehò, *Introduzione a Aristotele, Problemi meccanici*, p. 51). In any case, unanimous is the acknowledgment that the treatise would read the thought of Aristotle and Galileo considers it as being Aristotelian. This is why, in the present paper, the treatise will be referred to as being "Aristotelian".

⁶ Galileo recognised the *Quaestiones mechanicae* as an authentic work by Aristotle, and certainly this work played an important role in the scientific production of the scientist from Pisa. Still today, the work remains one of the least studied peripatetic texts. It has been available in the Italian translation since 2000, edited by Maria E. Bottecchia Dehò, whereas the first modern critical edition dates to 1982 (see Aristot., *MHXANIKÁ*, ed. M.E. Bottecchia, Padova, Antenore, 1982). This is worth to remark it if one considers that more than 400 years had gone by since the Guarino edition, published in Modena in 1573.

⁷ Cited for the first time in the *De motu antiquiora* (1590) in a marginal note to Problem 24, the *Quaestiones mechanicae* are a determining component in the drafting of the *Mecaniche*, they appear in *Discorso intorno alle cose che stanno in su l'acqua* (1612) and are openly cited in the *Dialogue Concerning the Two Chief World Systems* (1632), with reference to Problem 8 and the *Incipit*. Above all, what is most interesting is that the text is used by Galileo, and even lies at the base of numerous passages of *Discourses and Mathematical*

Especially, the *Quaestiones mechanicae*, as interpreted in the extensive body of 16th-century literature on the subject, had an extensive and explicit influence on Galileo's *Discourses and Mathematical Demonstrations Relating to Two New Sciences* (1638). It is especially interesting to see how Galileo, known for his anti-Aristotelian statements, at the beginning of the *seconda giornata*, explicitly declares that he found in the *Quaestiones mechanicae* the correct explanation for the operation of simple machines:

Salv. [...] In this discussion I shall take for granted the well-known mechanical principle which has been shown to govern the behavior of a bar, which we call a lever, namely, that the force bears to the resistance the inverse ratio of the distances which separate the fulcrum from the force and resistance respectively.

Simp. This was demonstrated first of all by Aristotle, in his *Mechanics*.

Salv. Yes, I am willing to concede him priority in point of time.⁸

In 1638, Galileo wrote to Elia Diodati stating that he was planning to write a dialogue with a series of annotations (*postille*) to the *Quaestiones mechanicae*, thus expressing his interest in this work by Aristotle.

Unfortunately, the dialogue was never actually written, making it difficult to determine Galileo's general attitude towards the problematic treatise. Nonetheless, it is possible to make several observations about Galileo's attitude toward Aristotle with regard to one problem in particular. This is the "Problem of the breaking strength of materials" (Problem XVI),⁹ one

Demonstrations Relating to Two New Sciences (1638). See Galileo Galilei, *Opere di Galileo Galilei*, a cura di A. Favaro, Firenze, Edizione Nazionale, 1890-1909.

⁸ Galileo Galilei *Dialogue Concerning Two New Sciences*, from the Italian and Latin to English by H. Crew, A.D. Salvio, New York, Northwestern University, 1939. Beginning of the second day, 152. The original text is: "Salv. Nella quale specolazione io piglio come principio noto quello che nelle mecaniche si dimostra tra le passion del vette, che noi chiamiamo leva, cioè che nell'uso della leva la forza alla resistenza ha la proporzion contraria di quella che hanno le distanze tra 'l sostegno e le medesime forza e resistenza. Simp: Questo fu dimostrato da Aristotile, nelle sue Mecaniche, prima che da ogni altro. Salv: Voglio che gli concediamo il primato nel tempo" (see Galileo Galilei, *Opere di Galileo Galilei*, vol. 8, 1898).

⁹ Much research was done between the 1400s and the 1600s on the resistance of beams. Leonardo da Vinci can be considered as one of Galileo's precursors. He compared the resistance of beams made of the same material but of different dimensions in order to determine a direct or inverse proportion between the bearing capacity and the height, thickness and length. As said before, other scientists preceded

of 35 questions posed and solved by the author of the *Quaestiones mechanicae* in his work. Within this problem the notion of individual limit, which appears in this paper's title, is central.

This paper addresses first of all the exposition of the problem put forth by Galileo, and then looks at the solution he proposed. After this, Galileo's proposal is compared to the one made by Aristotle. The statement found in the *Quaestiones mechanicae* reads as follows: "Why is it that the longer a board is, the weaker it gets?"¹⁰ Galileo uses this question as a starting point for elaborating his own "theory of the breaking strength of materials" in the second day of his *Dialogue*. Also in the first day he uses it to investigate the fragility of objects and to examine the solutions proposed by past authors. Before Galileo, in fact, there was a belief that different architectural structures that are geometrically similar would have identical static properties. Indeed, geometric measurements were the only criteria used by Renaissance architects.¹¹ As we will see, Galileo profoundly renewed this branch of science, but was resolute in maintaining the idea that the external shape of a body (understood in terms of perimeter, size and volume) affects the resistance of the body itself. This concept can be defined as individual limit, but a better definition of the term will follow in the second part of this paper.

First of all, it seems useful to define fragility given the significant difference between the contemporary mechanical theory and that of both Galileo and Aristotle. It is well known that in Galileo's time the 'fragility of a body' was analysed in mechanical terms of action and reaction and in geometrical terms of external form. Today it is explained

Galileo in their observations of mechanical structure, but Galileo was the first to make important steps in the theory of solidity and fragility.

¹⁰ Galileo, *Dialogue Concerning Two New Sciences*, 165; see also, Aristot. *Mech.* 853a5-6. The original text is: "Διὰ τί, ὅσω ἂν ἡ μακρότερα τὰ ξύλα, τοσούτῳ ἀσθενέστερα γίνεται".

¹¹ B.T. Vinaty, "La fragilità degli oggetti secondo Galilei", <http://www.cra-cma.it/fragilit%C3%A0.doc>.

by the “infinitesimal strain theory”. This theory implements Galileo’s deductions, while adding a more complex explanation of strain.¹²

Galileo’s Solution to the Problem of the Strength of Materials

Galileo’s explanation of the problem and its solution are found in the first and second days respectively of the *Dialogue Concerning Two New Sciences*. In the first day the three participators in the dialogue, i.e. the noble Florentine Salviati, the Venetian patrician Sagredo and the ‘Aristotelian’ Simplicius, discuss the “resistance of bodies to be broken”. In the second day, the three characters discuss the ‘cause’ of the resistance.

During the formulation of the problem, on day one,¹³ Galileo raises a paradox he came across during his technical experience, which became the basis of his research on the resistance of materials.¹⁴

Salv. You refer, perhaps, to that last remark of his [the vary of the proportion affects the strength] when we asked the reason why they employed stocks, scaffolding and bracing of larger dimensions for launching a big vessel than they do for a small one; and he answered that they did this in order to avoid the danger of the ship parting under its own heavy weight, a danger to which small boats are not subject?

Sagr. Yes, that is what I mean; and I refer especially to his last assertion which I have always regarded as a false, though current, opinion; namely, that in speaking of these and other similar machines one cannot argue from the small to the large,

¹² The explanation utilizes a complex mathematical model in order to represent the macroscopic behaviour of an object when exposed to given loads and constraints. In an isotropic body, the geometric description of the state of movement is represented in mathematical terms by a deformation vector defined by six components. The components are linked to the various partial derivatives of the movement function with respect to the spatial coordinates. The mechanical definition of actions and reactions can be measured by a tension vector defined by six components linked to the values of the actions and the values of the restraints imposed on the body.

¹³ Galileo, *Dialogue Concerning Two New Sciences*, 50, 51 and 52.

¹⁴ See *ibid.*, 50, where Galileo himself specifies that these observations had been inspired by his frequent visits, while living in Padua, to Venice’s ‘Arsenale’ (dockyard).

because many devices which succeed on a small scale do not work on a large scale.¹⁵

The paradox comes about by calling to mind the image of a ship whose dimensions are large enough to be cohesive and sturdy in all parts. The hypothesis is to reproduce the same ship on a larger scale using the same construction material and, moreover, the same proportions. He establishes that the larger ship would ‘not’ be stronger than the smaller. It would be instead much weaker.¹⁶

The innovative quality of Galileo’s thinking can already be seen in these statements. In fact, before Galileo’s contribution to mechanics, the shape and material of an object were the only variants that were believed to determine its solidity or fragility. Contrarily, Galileo finds certain relationships between the resistance of the material and the dimensions of the structure apart from the shape of the object.¹⁷ It is for this reason that Galileo makes the characters of his dialogue surprisingly acknowledge that the *gran galeazza*, i.e. the bigger ship, would break apart more easily, despite being proportionate to the smaller.

He later emphasizes that this fact seems to contradict the principle that geometry can solve the problem of fragility when analysing figures. Like

¹⁵ *Ibid.*, 50. The original text is: “Salv. V. S. vuol forse dire di quell’ultimo pronunziato ch’ei profferì mentre ricercavamo d’intendere per qual ragione facevano tanto maggior apparecchio di sostegni, armamenti ed altri ripari e fortificazioni, intorno a quella gran galeazza che si doveva varare, che non si fa intorno a vasselli minori; dove egli rispose, ciò farsi per evitare il pericolo di direnarsi, oppressa dal gravissimo peso della sua vasta mole, inconveniente al quale non son soggetti i legni minori? Sagr. Di cotesto intendo, e sopra tutto dell’ultima conclusione ch’ei soggiunse, la quale io ho sempre stimata concetto vano del vulgo; cioè che in queste ed altre simili machine non bisogna argumentare dalle piccole alle grandi, perché molte invenzioni di machine riescono in piccolo, che in grande poi non sussistono” (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8).

¹⁶ In fact, as the Galilean Salviati states, the larger ship even runs the risk “di arenarsi, oppressa dal gravissimo peso della sua vasta mole, inconveniente al quale non son soggetti i legni minori?” (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8).

¹⁷ This deduction must have appeared astonishing in an age in which, as said before, it was believed that the resistance of a body was connected to its shape, defined as the proportions among its parts. Consequently, two objects of the same material and identical proportions were considered to be equally fragile or strong. The shape is defined as a reciprocal proportion of its parts. See S. Di Pasquale, *L’arte del costruire – tra conoscenza e scienza*, Venezia, Marsilio Editori, 1996.

Sagredo points out,¹⁸ this is because mathematical demonstrations are based on geometry, and geometry does not consider the true size of shapes but considers them to be ‘ideal’:

Sagr. [...] Now, since mechanics has its foundation in geometry, where mere size cuts no figure, I do not see that the properties of circles, triangles, cylinders, cones and other solid figures will change with their size. If, therefore, a large machine be constructed in such a way that its parts bear to one another the same ratio as in a smaller one, and if the smaller is sufficiently strong for the purpose for which it was designed, I do not see why the larger also should not be able to withstand any severe and destructive tests to which it may be subjected.¹⁹

In the end, as Salviati states, experience proves that a fault in the materials alone is not enough to explain the difference between an ideal machine and a real machine. However, one single fault is able to contaminate the purest of geometrical demonstrations. The passage reads as follows:

Salv. The common opinion is here absolutely wrong. Indeed, it is so far wrong that precisely the opposite is true, namely, that many machines can be constructed even more perfectly on a large scale than on a small; thus, for instance, a clock which indicates and strikes the hour can be made more accurate on a large scale than on a small. There are some intelligent people who maintain this same opinion, but on more reasonable grounds, when they cut loose from geometry and argue that the better performance of the large machine is owing to the imperfections and variations of the material. Here I trust you will not charge me with arrogance if I say that imperfections in the material, even those which are great enough to invalidate the clearest mathematical proof, are not sufficient to explain the deviations observed between machines in the concrete and in the abstract. Yet I shall say it and will affirm that, even if the imperfections did not exist and matter were absolutely perfect, unalterable and free from all accidental

¹⁸ The participant in the dialogue who most often makes shrewd observations.

¹⁹ Galileo, *Dialogue Concerning Two New Sciences*, 50. The original text is: “Sagr. Ma essendo che tutte le ragioni della meccanica hanno i fondamenti loro nella geometria, nella quale non veggo che la grandezza e la piccolezza faccia i cerchi, i triangoli, i cilindri, i cono e qualunque altre figure solide, soggette ad altre passioni queste e ad altre quelle; quando la machina grande sia fabricata in tutti i suoi membri conforme alle proporzioni della minore, che sia valida e resistente all’esercizio al quale ella è destinata, non so vedere perché essa ancora non sia esente da gl’incontri che sopraggiugner gli possono, sinistri e destruttivi” (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8).

variations, still the mere fact that it is matter makes the larger machine, built of the same material and in the same proportion as the smaller, correspond with exactness to the smaller in every respect except that it will not be so strong or so resistant against violent treatment; the larger the machine, the greater its weakness. Since I assume matter to be unchangeable and always the same, it is clear that we are no less able to treat this constant and invariable property in a rigid manner than if it belonged to simple and pure mathematics. Therefore, Sagredo, you would do well to change the opinion which you, and perhaps also many other students of mechanics, have entertained concerning the ability of machines and structures to resist external disturbances, thinking that when they are built of the same material and maintain the same ratio between parts, they are able equally, or rather proportionally, to resist or yield to such external disturbances and blows. For we can demonstrate by geometry that the large machine is not proportionately stronger than the small. Finally, we may say that, for every machine and structure, whether artificial or natural, there is set a necessary limit beyond which neither art nor nature can pass; it is here understood, of course, that the material is the same and the proportion preserved.²⁰

²⁰ See *ibid.*, 50-51. The original text is: “Salv. Il detto del vulgo è assolutamente vano; e talmente vano, che il suo contrario si potrà profferire con altrettanta verità, dicendo che molte machine si potranno far più perfette in grande che in piccolo: come, per esempio, un oriuolo, che mostri e batta le ore, più giusto si farà d’una tal grandezza che di un’altra minore. Con miglior fondamento usurpano quel medesimo detto altri più intelligenti, i quali della riuscita di tali machine grandi, non conforme a quello che si raccoglie dalle pure ed astratte dimostrazioni geometriche, ne rimettono la causa nell’imperfezione della materia, che soggiace a molte alterazioni ed imperfezioni. Ma qui non so s’io potrò, senza inciampare in qualche nota di arroganza, dire che né anco il ricorrere all’imperfezioni della materia, potenti a contaminare le purissime dimostrazioni matematiche, basti a scusare l’inobbedienza delle machine in concreto alle medesime astratte ed ideali: tuttavia io pure il dirò, affermando che, astraendo tutte l’imperfezioni 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 dell’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 e resistenza contro alle violente invasioni; ma quanto più sarà grande, tanto a proporzione sarà più debole. E perché io suppongo, la materia essere inalterabile, cioè sempre l’istessa, è manifesto che di lei, come di affezione eterna e necessaria, si possano produr dimostrazioni non meno dell’altre schiette e pure matematiche. Però, Sig. Sagredo, revochi pur l’opinione che teneva, e forse insieme con molti altri che nella meccanica han fatto studio, che le machine e le fabbriche composte delle medesime materie, con puntuale osservanza delle medesime proporzioni tra le loro parti, debban essere egualmente, o, per dir meglio, proporzionalmente, disposte al resistere ed al cedere alle invasioni ed impeti esterni, perché si può geometricamente dimostrare, sempre le maggiori essere a proporzione men resistenti che le minori; sì che ultimamente non solo di tutte le machine e fabbriche artificiali, ma delle naturali ancora,

In this excerpt it appears evident that, according to Galileo, one cannot consider only the ideal shape of a solid when evaluating its hypothetical strength. In fact, Galileo had come to the conclusion that one cannot go from a geometrical similitude to a mechanical similitude as if they were one and the same. The reason for this is that a geometrical similitude is based on the fact that a shape can be reproduced in any scale without modifying any of the geometrical characteristics. On the contrary, a geometrical shape cannot acquire mass, traditionally seen as an amount of matter or *quantitas materiae*. Consequently, the only solution found is to accept a discontinuity between the simple geometric proportions and the effective resistance of bodies. Moreover, the *Dialogue* establishes the necessity to find the exact ratio between the breaking resistance of solids and their length, diameter, shape, etc. It also states that this ratio should be found according to what experience has taught.

According to Galileo, an explanation cannot be reached through observation alone; reflecting on the lesson gained through observation, “especially if contrary to the predictions made by science”, leads to the understanding of the true ‘complexity’ of the problem and to the basis for the elaboration of adequate hypotheses.²¹ Indeed, the concept of ‘complexity’ best reflects Galileo’s position on the problem of the breaking resistance of materials.

Evidently, the discussion that takes place during the first day of the *Dialogue* constitutes an excellent introduction to the theory of fragility. The mechanical similitude has the purpose of determining what conditions make it possible to obtain identical degrees of ‘specific resistance’ to breaking in nature, in real constructions and in reduced-scale models. The solution to this problem is that the ratios of the shape

sia un termine necessariamente ascritto, oltre al quale né l’arte né la natura possa trapassare: trapassar, dico, con osservar sempre l’istesse proporzioni con l’identità della materia” (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8).

²¹ It must be specified that the observation Galileo refers to in these lines, which constitutes the basis for the ‘new science’, has nothing to do with traditional science’s observation.

must be varied in order to obtain the same solidity, and at the same time, the dimensions of the structure must be taken into account. In fact, during his stay at Padua (1592-1610), Galileo began investigating the effects of gravity. At that time, he was convinced that the primary requirement for an object to not be fragile, and therefore not be broken, was that it had to be able to easily support its own weight.

Galileo meditated extensively on these observations until he became convinced that the weight and size of an object were factors that contributed to the object's solidity and fragility.

Equally, within the *Dialogue*, these observations are found at the beginning of day two when, after the author has examined various mathematical principles involving physics and has defined several general laws of movement, at odds with the peripatetic tradition, the content of the *Dialogue* specifically addresses statics. This section is closely related to the inquiries contained in the *Mecaniche* dated 1593, given that the central theme of this part of the *Dialogue*, i.e. the resistance of metals, is connected to the lever principle. Even the method of analysis and exposition in the *Dialogue* is linked to the geometrical-proportional method used in the *Bilancetta* and in the *Mecaniche*. This makes the statements of the *seconda giornata* more relevant. In fact, they provide important clarifications as to his methods and his perception of nature, which is mechanistic and contrary to any finalistic conception. As stated above, during the second day, Galileo returns to the problem of measurement:

Salv. Clearly then if one wishes to maintain in a great giant the same proportion of limb as that found in an ordinary man he must either find a harder and stronger material for making the bones, or he must admit a diminution of strength in comparison with men of medium stature; for if his height be increased inordinately he will fall and be crushed under his own weight. Whereas, if the size of a body be diminished, the strength of that body is not diminished in the same proportion; indeed the smaller the body the greater its relative strength. Thus a

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small dog could probably carry on his back two or three dogs of his own size; but I believe that a horse could not carry even one of his own size.²²

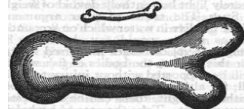


Figure 1

In this passage, Galileo discusses the general problem of the resistance of materials at their breaking point, comparing the resistance of a bone to that of a cylinder. He attempts to find the maximum length at which both the bone and the cylinder would break under their own weight. In so doing, Galileo reaches a paradoxical result, i.e. that a hollow tube would be sturdier than a solid tube, provided that the two were of the same length and material.²³ In other words, Galileo believed that a body's resistance is connected to its structure. Therefore, if an object is enlarged and is still made of the same material, the structure must change so that the object will not become more fragile. This is why it can be stated that, according to the philosopher, the morphologic growth of any living being, just like the building of any manmade construction, requires an accurate 'measuring'.

We see that a 'new science' is being born, because Galileo has revolutionized the traditional concept of resistance, making it mechanical, geometrical and physical. In fact, rupture is no longer seen

²² Galileo, *Dialogue Concerning Two New Sciences*, 169-170. The original text is: "Salv. Dal che è manifesto, che chi volesse mantenere in un vastissimo gigante le proporzioni che hanno le membra in un uomo ordinario, bisognerebbe o trovar materia molto più dura e resistente, per formare l'ossa, o vero ammettere che la robustezza sua fusse a proporzione assai più fiacca che ne gli uomini di statura mediocre; altrimenti, crescendogli a smisurata altezza, si vedrebbero dal proprio peso opprimere e cadere. Dove che, all'incontro, si vede, nel diminuire i corpi non si diminuir con la medesima proporzione le forze, anzi ne i minimi crescer la gagliardia con proporzion maggiore: onde io credo che un piccolo cane porterebbe addosso due o tre cani uguali a sé, ma non penso già che un cavallo portasse né anco un solo cavallo, a se stesso uguale" (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8).

²³ Galileo could have found numerous example of this in both plants (blades of grass) and animals (bones and organic cavities).

as the casual result of an impact, rather it is seen as a process of internal structural mechanics. Furthermore, in this text Galileo poses the question “how can a body surface area adapt to volume through certain modifications of form?”. He answers by saying that a constant ratio between the mass and the surface must be maintained. Moreover, even if not explicitly stated, the scientist explains an important morphologic criterion in his *Dialogue*: the more compact a body is, the more resistant it is.²⁴

It has been said that Galileo’s solution to the problem of the resistance of solid bodies to fracture presents several important characteristics. Galileo was the first to understand that everything has its own ‘magnitude’, and was also the first to attribute certain intrinsic properties to matter and to mention the existence of a large number of mechanical laws.²⁵ However, this paper intends to address another matter, or rather a specification of this matter, namely the differences between the solution proposed by Aristotle and the one proposed by Galileo. As I shall show later, the crucial topic related to Galileo’s treatment of the resistance of solid bodies to breaking is the cause of their cohesion, i.e. the structure of the matter.

As a matter of fact, Galileo’s philosophy of nature is radically different from the Aristotelian one. For what concerns the object of the present paper, Galileo distanced himself from Aristotle and from ‘antiquiores philosophi’, according to whom “una omnium corporum sit materia, et illa quidem graviora sint quae in augustiori spatio plures illius materiae particulas includerent”,²⁶ suggesting a different description of the matter.²⁷ With regard to this, already in the manuscript known with

²⁴ In fact, the coefficient of compactness is a linear coefficient given by: volume/area. Using Galileo’s terminology, we can state that the experience of solidity, from the point of view of ‘pure mechanics’, must be justified by the isoperimetric theorem of geometry.

²⁵ It cannot be denied that Galileo’s ideas related to the solidity and fragility of his “new science of resistance” are innovative; but what he lacked was a true “physics of the solid state”. His science maintains a prevalence of structural mechanics based on geometric reasoning, whereas it gives little space to the physical properties of material.

²⁶ Galileo Galilei, *Opere di Galileo Galilei*, vol. 1, p. 252.

²⁷ The literature on Galileo’s conception of the matter is very extensive. Anyway, it is important to mention at least U. Baldini, “La struttura della materia nel

the title *De motu antiquiora*,²⁸ Galileo stated his own conception of the matter in terms of homogeneity,²⁹ which, while explicitly attacking Aristotle,³⁰ approached ancient Greek atomism.³¹

Galileo rejected the belief according to which the characteristics of the matter (for example the strength) are to be intended as ‘qualities’ of the matter itself, because his concept of matter or of body substance implies the concepts of form, of relation with other bodies, of existence in a time and place, of stillness and movement, of contact or not with another body.³² Galileo was apparently led by the assumption that

pensiero di Galileo”, *De Homine*, 56-58, 1977, p. 1-74; Z. Biener, “Galileo’s first New Science: The science of matter”, *Perspectives on Science*, 12, 2004, p. 262-287; P. Galluzzi, *Tra atomi e indivisibili. La materia ambigua di Galileo*, Firenze, Olschki, 2001.

²⁸ This piece of work did not reach us; however the title is proven by Vincenzo Viviani (Galileo Galilei, *Opere di Galileo Galilei*, vol. 1, p. 245).

²⁹ See *ibid.*, p. 362: “Omnium corporum una est materia, eaque in omnibus gravis”.

³⁰ The Aristotelian philosophy is a theory of the elements of the pluralist type which differentiates from the other monist theories by the Presocratics and approaches what had been stated by Empedocles. In fact, the latter was the author of the first ‘pluralist’ philosophy, which considered the matter as made up of four fundamental elements: earth, air, water, and fire and it considered the couple love/hate as the beginning of the movement of such elements. See G. Galli, *L’idea di materia e di scienza fisica da Talete a Galileo*, Torino, G. Giappichelli Editore, 1963 and S. Le Bihan, *Conceptions de la Matière*, <<http://www.soaziglebihan.org/documents/CH284/CH284-MATIERE-1.pdf>>. See also Z. Biener, “Galileo’s first New Science: The science of matter”, *Perspectives on Science*, 12, 2004, p. 262-287; R. Hall, *Da Galileo a Newton*, Milano, Feltrinelli, 1973; E. Mach, *La meccanica nel suo sviluppo storico-critico*, Torino, Bollati Boringhieri, 1968.

³¹ Galileo denies the qualitative distinction of the elements proposed by Aristotle and mentions the ancient atomism theories. For instance, during the first day of the *Discourses and Mathematical Demonstrations Relating to Two New Sciences*, dealing with the cohesion of the matter, Simplicius hints at “quel certo filosofo antico”, author of the texts “discordi dalla mente temperata e ben organizzata di Vostra Signoria, non solo religiosa e pia, ma cattolica e santa”. However, during the whole discussion on the primary and secondary qualities of the matter, he never uses the term ‘atom’, but speaks for example of ‘corpicelli minimi’, ‘minimi quanti’, which are in any case the smallest parts of a well-defined substance and not the final components of the matter.

³² See P. Rossi, “Galileo Galilei”, in F. Abbri (ed.), *Storia delle scienze moderna e contemporanea, 1: Dalla rivoluzione scientifica all’età dei lumi*, Milano, TEA, 2000, p. 193-227, p. 207. He notes: “Se non fossimo provvisti di sensi, la ragione e l’immaginazione umana non giungerebbero mai a sospettare l’esistenza di tali proprietà” which “sono soltanto dei nomi”. In this case, with ‘proprietà’ (characteristics) one could also mean dry, solid etc.

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scientific knowledge distinguishes what in the world is objective and real from what is subjective and relative to the perception of the senses.

To summarize, Galileo's theory of the strength of materials was the result of a deep conceptual devolution of the notion of matter, based on a new general conception of the physical universe,³³ and on the detachment from a conception which traced back the physical characteristics of an object to some qualities which are internal to the matter of the object itself.³⁴

The Confrontation with Aristotle

It is now important to return to the question under exam, which is the comparison between the thesis of Galileo and that of Aristotle. To the question "why objects break?", two answers can be given: the first proposes that objects are fragile in that they are subject to fracturing processes of structural mechanics; the second states that objects break because they are fragile. In this last case, the property of fragility is attributed to the object, in contrast to the solidity (*firmitas* in Latin) of the objects subject to fracturing processes of structural mechanics.³⁵ As discussed above, Galileo proposes the first solution; whereas the second is precisely the solution attributed to Aristotle, which was professed in Peripatetic natural philosophy from antiquity to the Middle Ages.

It is important to note that the traditional point of view must not be thought of as a mere verbalism, as if one were tautologically stating that "material objects break because they are fragile".

³³ As Paolo Rossi states (P. Rossi, "La filosofia meccanica", in *Storia della scienza moderna e contemporanea, 1: Dalla rivoluzione scientifica all'età dei lumi*, p. 229-258, p. 230): "Si tratta [...] di modi nuovi di determinare i fini, i compiti, gli scopi della conoscenza della natura".

³⁴ In fact, as already said, the modern science was born thank to an analysis capable of abstractions, or rather capable of leaving aside the level of common sense, of the sensible qualities and of immediate experience. In short: modern science was born thank to a 'mathematization' of physics.

³⁵ See E. Benvenuto, *La scienza delle costruzioni e il suo sviluppo storico*, Firenze, Sansoni, 1981.

The Aristotelian answer to the problem, in reality, is based on the doctrine of the four elements and four sensitive properties. It is based on a physical science that investigates the sensitive qualities of matter. Aristotle addresses this concept in the second book of the treatise *De partibus animalium*³⁶ and in the second book of *De generatione et corruptione*.³⁷ In brief, several fundamental assumptions account for the Aristotelian concept. First of all, according to Aristotle, all material bodies on earth are made up of a mixture of four elements (στοιχεῖα): earth, water, air and fire. Each element is associated with two of the following four properties: hot, cold, dry (ξηρόν) and wet (ύγρόν). Dry is considered to be solid, whereas wet is considered to be fluid, and then the properties of thinness, viscosity and softness derive from the wet/fluid, whereas thickness, friability and hardness come from the dry/solid.³⁸ The following diagram makes the notion intuitive:

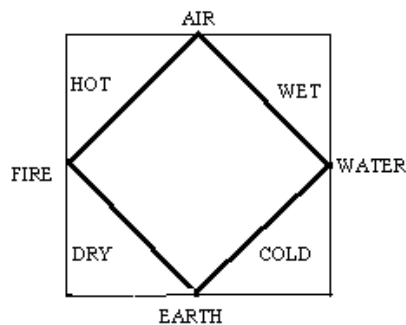


Figure 2

³⁶ Aristot. *De part. an.* 2.1.646a7-b9.

³⁷ Aristot. *De gen. et corr.* 2.1-8.328b1-335a25.

³⁸ Therefore, all other proprieties of matter must be traced back to wet and dry. For example, solidity is seen by the Stagirite as the property of a body to resist under pressure and not break into pieces. Something that is completely solid, due to the lack of fluidity, is solidified or stiff. See G.R. Giardina *Introduzione in Aristotele, Sulla generazione e la corruzione*, introduzione, traduzione e note di G.R. Giardina, Roma, Aracne, 2008, p. 70: “Gli elementi della tradizione, che Aristotele considera corpi misti, sono anch’essi contrari fra loro, a seconda che abbiano totalmente contrarie tutte e due le proprietà che li costituiscono”.

Therefore, ‘air’ is hot and wet/fluid, ‘water’ is cold and wet/fluid, ‘earth’ is cold and dry/solid, and ‘fire’ is hot and dry/solid. According to Aristotle, all the other properties derive from the primary elements, and every property corresponds to a certain power (δύναμις), i.e. heaviness, lightness, density, rarity, roughness and smoothness, etc. In *De partibus animalium* he explains:

Three sorts of composition can be distinguished. First of all we may put composition out of the Elements (as some call them), viz. Earth, Air, Water, Fire; or perhaps it is better to say *dynameis* instead of Elements – some of the *dynameis*, that is, not all, as I have stated previously elsewhere. It is just these four, the fluid substance, the solid, the hot, and the cold, which are the matter of composite bodies; and the other differences and qualities – such as heaviness lightness, firmness looseness, roughness smoothness, etc. – which composite bodies present are subsequent upon these.³⁹

The Stagirite organises all the physical properties around two pairs of basic and opposite properties: hot and cold, and dry (or solid) and wet (or fluid). Moreover, he affirms in *De sensu et sensibilibus* that the primary characteristic of these two pairs derives from their tactile origin, since the sense of touch is the sense which best fits with materiality:

For magnitude, figure, roughness and smoothness, as well as the sharpness and bluntness found in material bodies, are generic objects of sensation which, if not discerned by all the senses, are common to sight and touch at least.⁴⁰

It can therefore be inferred that Aristotle views *firmitas* as a sensation in which many secondary notions converge, such as hardness,

³⁹ Aristot. *De part. an.* 2.1.646a12-20. The original text is: Τριῶν δ’ οὐσῶν τῶν συνθέσεων πρώτην μὲν ἂν τις θείη τὴν ἐκ τῶν καλουμένων ὑπὸ τινῶν στοιχείων, οἷον γῆς ἀέρος ὕδατος πυρός. Ἐτι δὲ βέλτιον ἴσως ἐκ τῶν δυνάμεων λέγειν, καὶ τούτων οὐκ ἐξ ἀπασῶν, ἀλλ’ ὡσπερ ἐν ἑτέροις εἴρηται καὶ πρότερον. Ὑγρὸν γὰρ καὶ ξηρὸν καὶ θερμὸν καὶ ψυχρὸν ὅλη τῶν συνθέτων σωμάτων ἐστίν· αἱ δ’ ἄλλαι διαφοραὶ ταύταις ἀκολουθοῦσιν, οἷον βᾶρος καὶ κουφότης καὶ πυκνότης καὶ μακρότης καὶ τραχύτης καὶ λειότης καὶ τᾶλλα τὰ τοιαῦτα πάθη τῶν σωμάτων.

⁴⁰ Aristot. *De sensu* 4.442b5-7. The original text is: μέγεθος γὰρ καὶ σχῆμα καὶ τὸ τραχὺ καὶ τὸ λείον, ἔτι δὲ τὸ ὄξύ καὶ τὸ ἀμβλύ τὸ ἐν τοῖς ὄγκοις, κοινὰ τῶν αἰσθήσεων ἐστίν, εἰ δὲ μὴ πᾶσῶν, ἀλλ’ ὀψευῶς γε καὶ ἀφῆς.

impenetrability and compactness.⁴¹ These notions are the consequence of certain basic properties, and thus of certain elements that make up the material, as he asserts in *De generatione et corruptione*.

For Aristotle, the resistance of a body is directly proportional to the cohesion of its parts, and is the result of the primary characteristics that belong to the material of which it is made. So, from a mechanical point of view, fragility is defined an imperfection of the material, and breakage becomes a natural process that corresponds to a physical interaction. Aristotle therefore believed that a rupture process takes place when force (*δύναμις*) is applied to resistance. The exact moment of rupture occurs when force surpasses resistance.

On the other hand, according to Galileo, fragility is nothing more than the surpassing of a critical resistance limit. His doctrine of fragility connects mechanical tension to deformation geometry and supposes that the ‘critical breaking point’ is the result of a rational, although complex equation, just as complex as any reality whose critical point is studied.⁴² Which explains the two different answers to the question “why objects break”. Aristotle answers that objects break because they are made of a

⁴¹ See P. Tannery, *Pour l'histoire de la science hellène*, Paris, Gauthier-Villars et C. Éditeurs, 1930.

⁴² This doctrine sets matter, dimension, size and many other coordinates as its variables. In fact, as Salvati explains on the first day: “Salv. [...] Therefore, [...] you would do well to change the opinion which you, and perhaps also many other students of mechanics, have entertained concerning the ability of machines and structures to resist external disturbances, thinking that when they are built of the same material and maintain the same ratio between parts, they are able equally, or rather proportionally, to resist or yield to such external disturbances and blows. For we can demonstrate by geometry that the large machine is not proportionately stronger than the small” (Galileo, *Dialogue Concerning Two New Sciences*, 51). The original text is: “Salv. Revochi pur l'opinione che teneva, e forse insieme con molti altri che nella mecanica han fatto studio, che le machine e le fabbriche composte delle medesime materie, con puntuale osservanza delle medesime proporzioni tra le loro parti, debban essere egualmente, o, per dir meglio, proporzionalmente, disposte al resistere ed al cedere alle invasioni ed impeti esterni, perché si può geometricamente dimostrare, sempre le maggiori essere a proporzione men resistenti che le minori; sì che ultimamente non solo di tutte le machine e fabbriche artificiali, ma delle naturali ancora, sia un termine necessariamente ascritto, oltre al quale né l'arte né la natura possa trapassare: trapassar, dico, con osservar sempre l'istesse proporzioni con l'identità della materia” (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8).

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material inclined to snapping and breaking. Galileo, on the other hand, answers that “it is the mechanical strain which causes an object to fracture”. Indeed, he maintains that the mechanical and physical properties of matter can have the quality of perfection in themselves, and also that perfect rigidity exists. He had made it clear that the breaking point is affected by more than just the shape of a body, and it occurs due to the existence of another, additional strain.⁴³

From Differences to Similarities: The Limit of Substances

Up to this point, the different solutions proposed by Aristotle and Galileo in relation to resistance and fragility of materials are clear. These differences can be traced back both to their respective scientific and philosophical peculiarities and to their historical distance. In fact, as William R. Shea states, the scientific revolution was an authentic revolution, because the Aristotelian net of ideas, which was dismantled during the 17th century, was more than a scientific hypothesis.⁴⁴ Every time a comparison between two philosophies or scientific stances is made, however, one should never take into consideration only the differences between the two, but also the similarities that bind them. Therefore, it is interesting to point out a fundamental variant in the Galilean theory of the sturdiness of bodies, i.e. the relationship between their size and the shape of their perimeter, which opens up a comparison of the two philosophers as regards not only their views on the problem of the resistance of bodies to breaking, but also the way in which both conceived the individual limit of each body (the subject of the present paper). I have shown that, according to Galileo, the resistance of a body depends on its shape, which is the combination of perimeter, volume

⁴³ Instead, modern physics implements and applies Galileo’s intuition by means of the finite element method.

⁴⁴ W.R. Shea, “Il contributo di Paolo Rossi a una nuova interpretazione della rivoluzione scientifica”, in A. La Vergata – A. Pagnini (eds), *Storia della filosofia, storia della scienza: saggi in onore di Paolo Rossi*, Scandicci (Firenze), La Nuova Italia, 1995, p. 5-21, p. 19: “I Discorsi e dimostrazioni matematiche intorno a due nuove scienze [...] contengono un nuovo modo di trattare le resistenze dei materiali”.

and size. In the title of this paper I have called this concept individual limit. During the *prima giornata* of his *Dialogue*, Galileo concludes the analysis of the problem by stating that all machines and constructions, either natural or manmade, have a necessary, established limit that neither skill nor nature can pass, even when maintaining the same materials and proportions.⁴⁵ The passage reads as follows:

Salv. [...] Finally, we may say that, for every machine and structure, whether artificial or natural, there is set a necessary limit beyond which neither art nor nature can pass; it is here understood, of course, that the material is the same and the proportion preserved.⁴⁶

Thus, the individual limit is a “term necessarily ascribed to everything” and indicates what Galileo defines as *gagliardia*, a concept that must be applied to every object to express its maximal virtuality and indicates the maximum dimensions it could reach without breaking. In fact, just in the text which was cited before, Galileo, by stating that every dimension is linked to a “strenght capacity”, defines the latter as *gagliardia*.⁴⁷

⁴⁵ This is the explanation given by the Galilean physics. As it is noted, Galileo explains the experience of breaking with a doctrine of the matter and with a doctrine of the strenght, linked to the proportions of the object. It is within the context of this second explanation that the notion of *gagliardia* is introduced. As it will be seen afterwards, Aristotle also will give the same two types of answer to the question “Why objects break?”. In fact, as it has been seen, the first answer is linked to his concept of matter, while the one which will be illustrated now is linked to the proportion of the object.

⁴⁶ Galileo, *Dialogue Concerning Two New Sciences*, 51. The original text is: “Salv. Si può geometricamente dimostrare, sempre le maggiori essere a proporzione men resistenti che le minori; sì che ultimamente non solo di tutte le machine e fabbriche artificiali, ma delle naturali ancora, sia un termine necessariamente ascritto, oltre al quale né l'arte né la natura possa trapassare: trapassar, dico, con osservar sempre l'istesse proporzioni con l'identità della materia” (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8).

⁴⁷ See Galileo, *Dialogue Concerning Two New Sciences*, 170. The original text is: “Salv. Dove che, all'incontro, si vede, nel diminuire i corpi non si diminuir con la medesima proporzione le forze, anzi ne i minimi crescer la gagliardia con proporzion maggiore” (Galileo Galilei, *Opere di Galileo Galilei*, vol. 8). Citing this passage in the previous section of this article, the term *gagliardia* was translated with the expression ‘relative strength’; now, instead, it is worth to linger over the term used by Galileo. In fact, on one side, the notion of *gagliardia* (*gagliardia*, *gagliardia*, *gagliardie*, *gaiardia*, *galliardia*, *gbagliardia*), in Tuscan and Venetian texts prior or contemporary to Galileo, it indicated, among other things, an idea of vigour and strenght (see Guido da Pisa, *Fatti di Enea*, c. 39, p. 70.16); on the other side, the adjective and noun to which it is linked: *gagliardo*

It really is around Galileo's concept of *gagliardia* that I will try to propose a parallel with Aristotle. However, to be able to do so, it is necessary to re-investigate the Aristotelian notion of strength and in particular the way in which he solves the Problem XVI of the *Quaestiones mechanicae*, from which Galileo himself had started his investigation.⁴⁸ Immediately after having formulated it,⁴⁹ Aristotle proposes a solution to it which has the form of an alternative, as it is highlighted by the interrogative disjunctive conjunction 'ή' ; indeed, at the end of the sentence seems to be implied: 'or not'.⁵⁰

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? Is it because the length of the wood in the act of raising it forms the lever, weight and fulcrum?⁵¹ This formulation is contained in the explanation supported by Aristotle in the prosecution of the treatment of the 'problem', which is worth citing.

For the first part of it, that which the hand raises, acts as a fulcrum, the part at the end is the weight. Consequently the greater the distance from the fulcrum the more it must bend; for the greater the distance from the fulcrum the greater the bending must be. So the ends of the bar must be raised. If, then, the bar bends, it will bend more the more it is raised (a condition which occurs in the case of long

(*chagliardo, gagiardi, gagiardo, gagliarda, gagliarde*), it was used in the same texts to define something or somebody "endowed with vigour, efficacy, power, strength" (see Boccaccio, *Ninfae*, c. 110.5, p. 248; Giovanni Villani, b. 9, c. 8, v. 2, p. 24.2).

⁴⁸ Aristot. *Mech.* 853a9-19. The original text is: "Διὰ τί, ὅσω ἂν ἡ μακρότερα τὰ ξύλα, τοσούτω ἀσθενέστερα γίνεται, καὶ κάμπτεται αἰρόμενα μᾶλλον, κἂν ἡ τὸ μὲν βραχύ, ὅσον δίπηχυ, λεπτόν, τὸ δὲ ἑκατὸν πηχῶν παχύ; ἢ διότι μοχλὸς γίνεται καὶ βᾶρος καὶ ὑπομόχλιον ἐν τῷ αἰρεσθαι τοῦ ξύλου τὸ μήκος;"

⁴⁹ *Ibid.*, 853a5-10. The original text is: "τὸ μὲν γὰρ πρῶτον μέρος αὐτοῦ, ὃ ἡ χεὶρ αἶρει, οἷον ὑπομόχλιον γίνεται, τὸ δ' ἐπὶ τῷ ἄκρῳ βᾶρος, ὥστε ὅσω ἂν ἡ μακρότερον τὸ ἀπὸ τοῦ ὑπομόχλιου, τοσούτω ἀνάγκη κάμπτεσθαι μᾶλλον. ὅσω γὰρ ἂν πλεον ἀπέχη τοῦ ὑπομόχλιου, τοσούτω ἀνάγκη κάμπτεσθαι μείζον. ἀνάγκη οὖν αἰρεσθαι τὰ ἄκρα τοῦ μοχλοῦ. ἐὰν οὖν ἡ καμπτόμενος ὁ μοχλὸς, ἀνάγκη αὐτὸν κάμπτεσθαι μᾶλλον αἰρόμενον. ὅπερ συμβαίνει ἐπὶ τῶν κάμπτομενος ὁ μοχλὸς, ἀνάγκη αὐτὸν κάμπτεσθαι μᾶλλον αἰρόμενον. ὅπερ συμβαίνει ἐπὶ τῶν ξύλων τῶν μακρῶν. ἐν δὲ τοῖς βραχέσιν ἐγγυὲς τὸ ἔσχατον τοῦ ὑπομόχλιου γίνεται τοῦ ἡρεμούντος".

⁵⁰ This formulation seems to be aporetic.

⁵¹ *Ibid.*, 853a5-10. Translation by W.S. Hett (Aristotle, *Minor Works*, translated by W.S. Hett, Cambridge (Massachusetts) – London (England), Harvard University Press, 1936.

pieces of wood); whereas in short pieces the end is closet to the fulcrum, which is at rest.⁵²

In Aristotle's explanation the object is transformed into a lever and is assimilated to a machine (μηχανή).⁵³ In fact, the Stagirite detects within it different parts and points, having different functions. Moreover, the explanation goes beyond the mere strength of the materials, which was discussed before.⁵⁴

The exposition of the problem of strength of materials presents peculiar characteristics, which are important to highlight, in order to build a comparison with Galileo's solution. Aristotle considered the problem focusing on just 'one' beam: in fact, although speaking of 'beams' as plural (τὰ ξύλα), he considers them like if they were a single one, without comparing themselves, and this happens because, for the Stagirite, similar structures behave similarly.⁵⁵ The only variables that Aristotle considers are the length (μακρότης) of the beam and the fact that this is raised (αἴρεσθαι).⁵⁶ He solves the problem by just proposing a change in the length of the object. Now, it is known that, from the point of view of Aristotelian philosophy, lengthening is linked to the notion of form. In fact, according to him, bodies are made up of matter and form, and matter constitutes the substratum of bodies and is endowed with certain properties. By means of the union (σύνολον) of matter and form,

⁵² Aristot. *Mech.* 853a10-19. Translation by W.S. Hett.

⁵³ On this topic, I refer to M.F. Ferrini, introduction to "Aristotele", *Meccanica*, a cura di M.F. Ferrini, Milano, Bompiani 2010, p. 67-95.

⁵⁴ Aristot. *Mech.* 858a23-b3. Here the notion of strength is tied to the property of the matter of not yielding (breaking). Generally, as seen above, Aristotle faces the problem of breaking by adopting the matter as a unique substratum: in fact, although it is made up by elements, it always remains equal to itself.

⁵⁵ Concerning this topic, it is important to note that Galileo, much like Aristotle, uses the image of beams to illustrate the problem, and that, perhaps, it is not a case that Aristotle speaks just about beams/pieces of wood. In fact, in Greek, the term beam/piece of wood (τὸ ξύλον) derives from the addition of the preposition σύν (att: ξύν = with, by means of) to the term ὕλη (wood, but, above all, matter); in other words, by speaking of beams Aristotle recalls the idea of a matter having in some manner a particular form.

⁵⁶ See Aristot. *Mech.* 254b5: Problem XXII. The verb αἴρεσθαι indicates the lifting but also the widening of something.

the imperfection of the material turns into the perfection of the concrete substance (σύνολον), thanks to the perfection of the form. The material part of the σύνολον, however, is imperfect and therefore can break.⁵⁷

Also because of this, Aristotle analyses matter always and just with respect to the form that it can adopt, for the form is the source of the determinateness of the substance.⁵⁸ In fact, with respect to all the bodies that are generated,⁵⁹ Aristotle states that their purpose is always constituted by their form and their species (ἡ μορφή και τὸ εἶδος).⁶⁰

Examining the variation of the length of the beam (and therefore the vary of its form), Aristotle allows one to guess the existence of a limit length (i.e.: form), namely the maximum length that allows the beam to resist and perform its potentials.⁶¹ Just the fact of considering the being with respect to its form, to determine its strength, allows one to guess the parallel we mentioned before between the two philosophers, recalling Galileo's notion of *gagliardia*, intended as individual limit. In fact, Aristotle introduces an idea that, in different fields, may have taken on similar meanings. This idea is *αὐτάρκεια*, translated as 'autarchy', 'self-sufficiency', 'independence', but it is a notion that in some works is used technically and indicates a different concept.

⁵⁷ The matter is, however, also puissance (i.e. predisposition to a certain form): δύναμις as opposed to ἐνέργεια. See P.-M. Morel, *De la matière à l'action. Aristote et le problème du vivant*, Paris, Vrin, 2007 and D. Quarantotto, *Causa finale, sostanza, essenza in Aristotele*, Napoli, Bibliopolis, 2005.

⁵⁸ See Aristot. *Metaph.* Z, 3.1029a9-30. Aristotle states that, if the substrate would not need the form, then the matter would be substance, but this is impossible as the requisite of the substance is the determinateness. See E. Berti, *Aristotele: dalla dialettica alla filosofia prima*, Milano, Bompiani 2004; W.T. D'Arcy, *Crescita e forma*, trans. J.T. Bonner, Torino, Bollati Boringhieri, 1992.

⁵⁹ That is not only the elements, but also the composed bodies. For what concerns the four elements, Aristotle states that their final purpose is their natural place (i.e. that to which they tend to). But their purpose identifies itself also with their form, being it represented from the set of properties which they adopt when they are a certain element (dry, cold, wet, hot etc).

⁶⁰ Aristot. *De gen. et corr.* 2.9.335b6-7. See E. Berti, *Nuovi studi aristotelici. II – Fisica, antropologia e metafisica*, Brescia, Morcelliana, 2005.

⁶¹ See M.L. Gill, *Aristotle on Substance: The Paradox of Unity*, Princeton, Princeton University Press, 1989.

It seems useful to cite such texts but, before doing so, I would like to explain the reason why I will refer to texts included in the *Politics* and in the biology of Aristotle. Such explanation lies in the fact that the Stagirite uses the notion of *αὐτάρκεια* as an homonym *πρὸς ἓν*,⁶² and therefore – beyond the specific context of usage – its meaning is far more complex. Elsewhere,⁶³ I have pointed out the complexity of the notion, which exceeds the contexts and which cannot be superficially interpreted.⁶⁴ I have argued that the notion of *αὐτάρκεια* is an homonym *πρὸς ἓν*:⁶⁵ homonym, because the predicate ‘autarchic’ (*αὐτάρκης*) has different meanings in the different statements, and because every science (politics, biology, first philosophy) uses the notion and makes it technical; *πρὸς ἓν* because the different meanings are nevertheless closely related to a primary meaning, i.e. related to one central point, one definite kind of thing (*πρὸς ἓν καὶ μίαν τινὰ φύσιν*).⁶⁶ In fact, among the

⁶² See Aristot. *Cat.* 1.1a; *Metaph.* Γ, 2.1003a33-34; *Eth. Eud.* 7.1236b23-26; 1236a15-16; *passim*. See A. Stevens, “La plurivocité de l’étant et de l’un”, in M. Narcy – A. Tordesillas (eds), *La “Métaphysique d’Aristote”. Perspectives contemporaines*, Paris, Vrin – Ousia, 2005, p. 49-58.

⁶³ See S. Gullino, “L’*autarkeia* et ses significations chez Aristote”, Tesi di Dottorato, Università degli Studi di Padova, Padova 2011.

⁶⁴ *Ibid.*, p. 259-268.

⁶⁵ This is a case of multivocals which are nevertheless associated. Aristotle’s favourite examples of homonymy *πρὸς ἓν* (or, core-dependent homonymy and associated homonymy: see about this: C. Shields, *Order in Multiplicity: homonymy in the philosophy of Aristotle*, Oxford, Clarendon Press, 1999, p. 35-39; 57-62) illustrate a kind of association which is especially useful in offering accounts of central philosophical concepts: “Everything which is healthy is related to health (*πρὸς ὑγίειαν*), some by preserving health, some by producing health, others by being indicative of health, and others by being receptive of health” (see Aristot. *Metaph.* Γ, 2.1003a34b1).

⁶⁶ Aristot. *Metaph.* Γ, 2.1003a33-34: “Τὸ δὲ ὄν λέγεται μὲν πολλαχῶς, ἀλλὰ πρὸς ἓν καὶ μίαν τινὰ φύσιν καὶ οὐχ ὁμωνύμως”. “There are many senses in which a thing may be said to ‘be’, but they are related to one central point, one definite kind of thing, and are not homonymous”. (Trans. W.D. Ross, in J. Barnes, *The complete works of Aristotle*, Princeton, Princeton University Press, 1984, p. 1584). That is ‘focal meaning’ or ‘focal connection’. See J. Owens, *The Doctrine of Being in the Aristotelian Metaphysics*, Toronto, Pontifical Institute of Mediaeval Studies, 1951; E. Berti, *L’unità del sapere in Aristotele*, Padova, Cedam, 1965; E. Berti, “Multiplicité et unité du bien selon EE I 8”, in D. Harlfinger – P. Moraux (eds), *Untersuchungen zur Eudemischen Ethik*, Berlin, Walter de Gruyter & Co., 1971, p. 157-184; C. Rossitto, *Riflessioni sulla struttura logica della filosofia*, Padova, Libreria Editrice Gregoriana, 1982; E.C. Halper, *One and Many in Aristotle’s Metaphysics*, The Central Books, Columbus, Ohio State University Press, 1989.

particular meanings of the term *αὐτάρκεια*, there is one focal meaning which is such that all the other are related to it, and for which the beings are defined as autarchic by virtue of this relation to it. What serves as a common term of reference among the many types of autarchy, i.e. as *μία ἀρχή* is the autarchy which is typical of the ‘principle’. Therefore, the unity (*ἕν*) which makes non-simply homonyms the many ways in which the *αὐτάρκεια* can be understood by saying that *αὐτάρκεια* is the possibility that a being has to realize its aim and to perform its possibilities. Therefore, in some ways, it is its limit, because under such a limit a being is not autarchic and, beyond such a limit, the being is not itself anymore.⁶⁷ To clarify what I mean, it is useful to return to the texts. In his *Politics*, for example, Aristotle states the following:

To the size of states there is a limit (*ἔστι τι καὶ πόλεως μεγέθους μέτρον*) as there is to other things, plants, animals, implements; for none of these retain their natural power when they are too large or too small, but they either wholly lose their nature, or are spoiled. [...] Clearly then the best limit of the population of a state is the largest number which is autarchic for the purposes of life (*πρὸς αὐτάρκειαν ζωῆς*), and can be taken in at a single view. Enough concerning the size of a state.⁶⁸

⁶⁷ It could be observed that all the activities that are defined as ‘self-sufficient’ by Aristotle are by him described as *ἐνέργειαι*. But *αὐτάρκεια* is not only a notion that refers to a modality in which *ἐνέργεια* is realized. In fact, if it is able to enclose all the examples that Aristotle suggests, it is because it is able to describe activities that articulate according to the structure itself of the *ἐνέργεια*. By means of the notion of *αὐτάρκεια*, in fact, Aristotle describes the realization of the identity between the dispatch and the aim. Therefore, it deals with immortal beings but also with mortal and corruptible beings, of which it defines that state for which they preserve themselves, beyond everything that could ‘limit their activity’, that is a consequence of their living in contingency.

⁶⁸ Aristot. *Pol.* 7.4.1326a35-1326b25. The original text is: *ἀλλ’ ἔστι τι καὶ πόλεως μεγέθους μέτρον, ὡς περὶ καὶ τῶν ἄλλων πάντων, ζώων φυτῶν ὀργάνων· καὶ γὰρ τούτων ἕκαστον οὔτε λίαν μικρὸν οὔτε κατὰ μέγεθος ὑπερβάλλον ἔξει τὴν αὐτοῦ δύναμιν, ἀλλ’ ὅτε μὲν ὄλιως ἔστερημένον ἔσται τῆς φύσεως ὅτε δὲ φαύλως ἔχον [...] δῆλον τοίνυν ὡς οὗτός ἐστι πόλεως ὄρος ἄριστος, ἢ μεγίστη τοῦ πλήθους ὑπερβολὴ πρὸς αὐτάρκειαν ζωῆς εὐσύννοπτος, περὶ μὲν οὖν μεγέθους πόλεως διωρίσθω τὸν τρόπον τούτον.* Please note that, in this passage, Aristotle, speaking of size and limit (*μεγέθους μέτρον*), does not intend to refer only to the πόλις, but to things (*τῶν ἄλλων πάντων*), animals (*τῶν ζώων*), plants (*τῶν φυτῶν*), implements (*τῶν ὀργάνων*). Consequently such a statement, although being it included in a treatise having as object the ‘political science’, can be valid for every substance.

The individual limit of the πόλις, and of the other substances, determines their autarchy, i.e. their maximum resistance and preservation.⁶⁹

According to Aristotle, αὐτάρκεια is a condition linked to the individual limit of every substance and is the perfect expression of all its properties, including both physical properties and properties of resistance. This concept could therefore be compared to the previously described Galilean concept of *gagliardia*.

Also in Aristotle's works on biology there seems to be a connection between his notion of autarchy and Galileo's *gagliardia*, seen as the limit of a body, which gives the body certain properties. For example, in his *De generatione animalium*, Aristotle observes that "the higher animals are more independent in their nature, so that they have greater size, and this cannot exist without vital heat", and he concludes that this happens by virtue of their αὐτάρκεια.⁷⁰ In the passage above, Aristotle makes it clear

⁶⁹ As it was underlined, the term which Aristotle uses in this passage to indicate the concept of limit-size –and which he connects to the notion of αὐτάρκεια,– is μεγέθους μέτρον. To deepen this concept and to better understand its link with the notion of αὐτάρκεια it seems useful to recall some statements by Aristotle, included in chapter 13 of book Δ of *Metaphysics* (see Aristot. *Metaph.* Δ, 13.1020a7-32). Here, he examines size (μέγεθος) listing the various meanings of the notion of quantity (ποσόν); he states in fact that big and small are characteristics *per se* of quantity (*ibid.*, 1020a23-24) "which, if it is measurable, is size" (*ibid.*, 1020a9-10). It will be discussed later on about the link that exists between the size of a substance and its strength (see following notes); at the moment please note just that Aristotle links the notion of αὐτάρκεια to that of size, that is to a quality itself measurable, that is measurable and geometrically definable (see Alexandri Aphrodisiensis *In Aristotelis Metaphysica Commentaria*, editio M. Hayduck, Berolini, Reimer, 1891, p. 397,12-13; Aristotele, *Metafisica*, introduzione, traduzione e commentario a cura di G. Reale, Milano, Bompiani, 2004, *ad loc.*). That is why αὐτάρκεια can be identified as a sort of individual limit and that is the explanation of the link which could be instituted between the notion of αὐτάρκεια and the Galilean of *gagliardia*.

⁷⁰ Aristot. *De gen. an.* 2.1.732a16-18: τούτου δ'αἴτιον ὅτι τὰ τιμιώτερα καὶ αὐταρκέστερα τὴν φύσιν ἐστίν, ὥστε μεγέθους μετεληφέναι. "The reason of this is that the higher animals are more independent in their nature, so that they have greater size, and this cannot exist without vital heat". (Trans. A. Platt in Aristotle, *On the Generation of Animals*, Adelaide, The University of Adelaide Library, 2005). Speaking of size which is epiphenomenon of animal autarchy, Aristotle states that this latter one allows animals to μεγέθους μετεληφέναι (from μεταλαμβάνω = participate; from which literally: 'participate to size', see Aristotele, *De la génération des animaux*, texte établi et traduit par P. Louis, Paris, Les Belles Lettres, 2002, *ad loc.*: "atteindre une grande taille"). On the link

that the autarchy of an animal is closely connected to its external form and size, since it directly influences both⁷¹. Therefore, in general, in both the Stagirite's and Galileo's thinking, 'natural substances', as opposed to geometrical objects, do not allow the independence of forms and sizes. Indeed, their size and individual limit concur in determining the resistance of a body and its internal force, i.e. its *αὐτάρκεια* and *gagliardia*.

In conclusion, one could state that both notions express eloquently the idea that in every body there exists an ultimate strength,⁷² which performs at its best its limit, its possibilities. It seems therefore that, beyond the undeniable differences between the two philosophers, the notions of *gagliardia* and of *αὐτάρκεια* testify a common conception, derived most probably from sensible observation.⁷³

between physical arguments and geometric explanations, see S.G. Seminara, "Problemata Physica XVII", in B. Centrone (ed.), *Studi sui Problemata Physica aristotelici*, Napoli, Bibliopolis, 2011, p. 143-174.

⁷¹ The sizing of natural beings – meaning the increase – is not casual but it is closely linked to the nature, to the development and to the fulfilment of each being. In fact, Aristotle defines 'fulfilled' under the dimensional profile what widens according to the three dimensions (Aristot. *De caelo* 1.1.268b2): the body so intended is in fact a perfect size (τέλειον μέγεθος). To deepen this concept it could be useful to examine the second problem of section 17 of the Aristotelian *Problemata Physica*. Here Aristotle focalises on the issue of the increase of natural realities just on the point of view of the dimensions of the bodies – length, width and depth. Now, as inferred from several passages of the *Corpus Aristotelicum* (see Aristot. *Metaph.* Δ, 13.1020a11-12; Ζ, 3.1029a14-15; Γ 1, 1053a24-26; *Phys.* 4.1.1029a4-6; *passim*), for Aristotle length (μήκος), width (πλάτος) and thickness (βάθος) are the variables which determine the quantitative characteristics of a substance. They are therefore sizes, quantities (ποσόν) apt to measure and to de-fine/de-limit an object quantitatively broad.

⁷² In this case: damaging stress.

⁷³ Galileo often cites a passage from the third book of *De Generatione Animalium* and he designates it as a good criterion to follow. In the passage, Aristotle notes that: "The facts, however, have not yet been sufficiently grasped; if ever they are, then credit must be given rather to observation than to theories, and to theories only if what they affirm agrees with the observed facts" (Aristot. *De gen. an.* 3.10.760b27-33. The original text is: Ἐκ μὲν οὖν τοῦ λόγου τὰ περὶ τὴν γένεσιν τῶν μελιττῶν τοῦτον ἔχειν φαίνεται τὸν τρόπον καὶ ἐκ τῶν συμβαίνειν δοκούντων περὶ αὐτάς· οὐ μὴν εἰληπταὶ γὰρ τὰ συμβαίνοντα ἱκανῶς, ἀλλ' ἐάν ποτε ληφθῆ τότε τῇ αἰσθήσει μᾶλλον τῶν λόγων πιστευτέον, καὶ τοῖς λόγοις ἐάν ὁμολογούμενα δεικνύωσι τοῖς φαινόμενοις). See W.A. Wallace, *Galileo's Logical Treatises*, Dordrecht, Kluwer Academic Publishers, 1992.

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