Croatian Journal of Philosophy
Vol. XVII, No. 52, 2018

The Function and Limit of Galileo's Falling Bodies Thought Experiment: Absolute Weight, Specific Weight and the Medium's Resistance

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The ongoing epistemological debate on scientific thought experiments (TEs) revolves, in part, around the now famous Galileo's falling bodies TE and how it could justify its conclusions. In this paper, I argue that the TE's function is misrepresented in this a-historical debate. I retrace the history of this TE and show that it constituted the first step in two general "argumentative strategies", excogitated by Galileo to defend two different theories of free-fall, in 1590's and then in the 1638. I analyse both argumentative strategies and argue that their function was to eliminate potential causal factors: the TE serving to eliminate absolute weight as a causal factor, while the subsequent arguments served to explore the effect of specific weight, with conflicting conclusions in 1590 and 1638. I will argue thorough the paper that the TE is best grasped when we analyse Galileo's restriction, in the TE's scenario and conclusion, to bodies of the same material or specific weight. Finally, I will draw out two implications for the debate on TEs.

Keywords: Scientific thought experiments, Galileo's falling bodies, *De Motu* (1590) and *Discorsi* (1638), eliminating causal factors, absolute and specific weights, medium's resistance.

1. *Introduction*

Galileo's *Discorsi* (1638) falling bodies TE has become a key case study in the epistemological literature on TEs, especially since Brown (1986) famously claimed that it is canonical case of what he labelled "platonic TE": it is both destructive and constructive. It is destructive since it refutes an old theory (*i.e.* Aristotle's theory of free-fall), it is also constructive since it establishes, in *a priori* fashion, a new law of nature (*i.e.* in void, *all* bodies free-fall at the same speed). Brown's analysis was met by Norton (1996) who denied this "platonic" power of the TE and argued that it is reducible to a deductive argument, a TE-argument, that is an argument with *irrelevant* and even *eliminable* particulars. Both Norton and Brown agree that the TE perfectly leads to its destructive conclusion in a deductive manner. In addition, if the TE leads to its constructive conclusion, Norton claims that the TE-argument could deductively lead to this conclusion as well. However, Norton argues that the TE-argument shows us that the TE only leads to its constructive conclusion if we add the following hidden assumption 8a: the speed of a falling body depends *only* on its weight (see 4). Which for Norton amounts to assuming vacuum, something Galileo could not do in the context of the TE, and thus this constructive conclusion is "at worst, a fallacious inference to a falsehood [when assumption 8a does not hold]; or, at best, valid only insofar as it is invoked *in special cases* in which assumption 8a holds, such as the fall of *very heavy, compact objects in very rare media*. This final step now looks more like a clumsy fudge or a stumble than a leap into the Platonic world of laws." (Norton 1996: 345, my emphasis).

Norton's concluding remark, apart from being in tension with his "elimination thesis"[1], since he seems to grant some important role for the particulars involved it this TE, elicit the need to analyse the function of the particulars involved in Galileo's TE: very heavy, compact spherical objects of the same material falling in a rare medium such as air. More generally, the literature on TEs suffers from a major omission in analysing this TE: it does not tackle Galileo's restriction, in the TE's scenario and conclusion, to bodies of the *same material*. This omission is not proper to the Norton/Brown debate but is found in most of the literature. Of course, we find here and there some mention. For instance, Gendler underlines in a footnote the "somewhat unfortunate practice of considering this thought experiment outside of both its historical and textual contexts" (Gendler 1998: 402, ft 8). She then briefly mentions this restriction, however without analysing it, since she believes that for the purpose of her discussion "this constraint is irrelevant" (403, ft 13). Even if she rightly concludes that the TE's function is refutational and claims that she doesn't "think that the thought experiment in question shows anything more than that natural speed is independent of weight" (419), this restriction should not be left unanalysed if we want to understand the function and limit of Galileo's TE and its role in both argumentative strategies.

[1] "Thought experiments are arguments which contain particulars irrelevant to the generality of the conclusion. Thus any conclusion reached by a good thought experiment will also be demonstrable by an argument which does not contain these particulars and therefore is not a thought experiment" (Norton 1991: 131).

This restriction has even puzzled many Galilean scholars. For instance, at the end of his historical analysis of Galileo's arguments and TEs ("experiences imaginaires") since the *De Motu* (1590), Alexandre Koyré states that "Galileo's mention of specific gravity—*and this, in a reasoning in which it has nothing to do*—is extremely curious. And even, historically, very important."[2] More recently, Palmieri (2005) and Van Dyck (2006) analysed the historical development of this TE and its restriction to bodies of the same material, which brought Palmieri to conclude that "[p]erhaps we need a new approach to the question of thought experiment, capable of integrating results from different disciplinary areas, such as, for instance, the history and philosophy of science and cognitive science. […] The all too clean baby of today's debate on the most beautiful thought experiment in the history of science [Galileo's TE] should definitely be thrown out, and the bathwater carefully analyzed." (Palmieri 2005: 238). Regrettably, this was not taken into account by most philosophers working on TEs. For instance, we still find in the Stanford entry on TEs (2017, substantively updated in 2014) and in Brown's second version of his book (2010), that "Galileo showed that *all* bodies fall at the same speed with a brilliant thought experiment" (my emphasis).

I am in total agreement with Palmieri that history of science should play a central, at least a much greater role in the philosophical debate on TEs. Indeed, we have the general impression that the epistemological literature on scientific TEs is mainly built on a-historical analysis of case studies. This is especially lamentable for Galileo's falling bodies because the epistemological literature takes this TE as a canonical case study, while the a-historical analysis of this TE yields wide disagreements about its conclusion(s), leading to divergences pertaining to its epistemic function. Thus, leading the epistemological literature on TE astray and turning an important debate into a red herring: the Norton/Brown debate on TEs revolves, in part, around how Galileo's TE justifies its conclusions, by direct a priori access to laws of nature or by being a deductive argument. Nevertheless, the TE's function is misrepresented as *revealing* and *justifying* a law of nature (Brown since 1986 and even in a sense in Norton's 1996 reply).

The philosophical literature is thus in need of a more careful historical analysis of Galileo's TE and the following questions answered, before trying to analyse if and how the TE could justify its conclusion(s): What is the TE's function (or intended conclusion) for Galileo? What is its role in Galileo (1590 and 1638)'s argumentative strategies? What is the function of the particulars involved in its scenario? What are the idealisations involved? Are these idealisations justified? Since vacuum could not be explicitly assumed in the TE and thus its scenario takes

[2] "La mention par Galilée de la gravité spécifique — et ce, dans un raisonnement où elle n'a que faire — est extrêmement curieuse. Et même, historiquement, très importante." (my emphasis and translation, Koyré 1960: 203).

place in plenum, then how did Galileo take into account the multiple effects of the medium's resistance? In case we assume vacuum (for modern readers), what conclusion could the TE lead to? Is this conclusion justified? All these questions could be easily answered once we tackle the more general one: *why is the TE restricted to bodies of the same material?*

This paper aims at analysing the function and limit of Galileo's falling bodies TE, which will provide answers to these questions. First in (2), I show that the TE's function is only refutational; it aims at refuting Aristotle's theory of free-fall, one of its two principles to be precise, by showing that the falling body's *absolute weight* could *not cause* divergences in the speed of free-falling bodies. I thus retrace Galileo's TE to its first occurrence in the *De Motu* (1590) which explicitly indicates Galileo's intention of "seeking causes of effects". Second in (3), I analyse Galileo's both argumentative strategies that led him to two incompatible theories of free-fall. It will be shown that the TE's restriction to bodies of the same material is best understood when placing the TE in both 1590 and 1638 argumentative strategies. I will argue that both strategies aimed at exploring potential causal factors affecting divergences in speed of free-falling bodies: the TE aimed at eliminating *absolute weight* as a causal factor, which explains Galileo's restriction to bodies of the same material, while both 1590 and 1638 subsequent arguments aimed at exploring *specific weight* as a causal factor, *with conflicting conclusions*. Third in (4), I analyse one small effect of the medium's resistance that could not be taken into account in the TE, even by Galileo's choice of particulars; *i.e.* the medium's disproportionate effect on the free-falling body's surface to absolute weight ratio. This shows that the TE only works either if we can assume vacuum or by placing the TE in the whole argumentative strategy, where this small effect of the medium's resistance is subsequently explained (which Galileo does in 1638) and thus could be ignored in the TE. Finally in (5), I summarize, draw out two implications for the debate on TEs and restate answers to the above questions.

2. *Absolute weight in the* De Motu *(1590) and the* Discorsi *(1638): same TE, same conclusion*

Galileo[3] first introduced his TE in the *De Motu*, an unpublished manuscript usually dated from the 1590's. The TE appears in a larger argumentative strategy intended to first refute Aristotle's theory of free-fall and then defend Galileo's own early theory.

Galileo starts by clarifying the concepts of "heaviness" and "lightness". He stresses that both should be understood by what we could

[3] Prior to Galileo, we find a similar TE in the work of Jean Baptiste Benedetti (1553) who imagines a scenario involving the fall of two equal bricks, by themselves and then attached (cf. Koyré 1960: 203).

call "specific weight" (even if Galileo is comparing equal volumes, not unit volumes of bodies), without explicitly defining the concept in the *De Motu*. Indeed, Galileo tells us that "a thing should be called heavier than another, if when a piece of it is taken, equal to a piece of the other, it is found to be heavier than the piece of the other" (Galileo 1590: 1).

Then Galileo distinguishes different ways in which "greater or lesser swiftness of [natural] motion comes about" (Galileo 1590: 14). This is best understood when we divide, following Galileo, Aristotle's theory of free-fall into two principles[4]: (i) natural speed is proportional to weight, (ii) natural speed is inversely proportional to the medium's resistance or "density":

> [I]nequalities in the slowness and swiftness of motion occur in two ways: for either the same mobile is moved in different media [*i.e.* according to Aristotle's principle (ii), the speed of a mobile is inversely proportional to the medium's resistance]; or the medium is the same, but the mobiles are different [*i.e.* according to Aristotle's principle (i), the speed of the mobile is proportional to its weight]. We will demonstrate shortly that in both cases of motion the slowness and swiftness depend on the same *cause*, namely, *the greater or lesser heaviness [i.e. specific weight] of the media and of the mobiles*; but first we will show that *the cause of such an effect* which has been conveyed by Aristotle is *insufficient*. (Galileo 1590: 14, my emphasis[5])

Galileo's aim is to be found in this passage: he is seeking the causes of inequalities of slowness and swiftness of motion. He first aims at showing that the causes conveyed by Aristotle are either false—principle (i)—or insufficient—principle (ii). Galileo then aims to propose an early theory of free-fall, according to which the speed of a free-falling body is *proportional to its specific weight* (to be precise, minus the specific weight of the medium, see 3.1). This is how he proceeds.

Galileo starts by arguing against principle (ii) which states "that the cause of the slowness of motion is the thickness of the medium, and that of the speed, its subtlety" (p.14). Galileo aims at showing that this cause is insufficient, and he demonstrates this by appealing to examples where bodies, such as an inflated bladder, fall slowly downwards in air, but fly very swiftly upward when let go from deep in water.

Then Galileo moves to principle (i), which is the purpose of the TE.

[4] This division will be again introduced in the *Discorsi*. For instance when Simplicio explains Aristotle's argument against motion in void, he claims that Aristotle: "first supposes bodies of different weights to move in the same medium; then supposes, one and the same body to move in different media. In the first case, he supposes bodies of different weight to move in one and the same medium with different speeds which stand to one another in the same ratio as the weights; so that, for example, a body which is ten times as heavy as another will move ten times as rapidly as the other. In the second case he assumes that the speeds of one and the same body moving in different media are in inverse ratio to the densities of these media; thus, for instance, if the density of water were ten times that of air, the speed in air would be ten times greater than in water." Galileo 1638/1914: [105–106] of the National Edition.

[5] All emphasis in the subsequent quotes from the *De Motu* and the *Discorsi* are mine.

This principle aims at describing the speed of mobiles falling in the same medium. For these mobiles, Galileo further distinguish between two cases:

> [D]ifference between two mobiles can happen in two ways: for *either they are of the same species*, as, for example, both lead, or both iron; and they differ in size: *or they are of different species*, e.g. one iron, the other wood; they then differ from one another either in size and heaviness, or in heaviness and not in size, or in size and not in heaviness. (Galileo 1590: 15)

This distinction is crucial for what follows. Galileo will first limit his arguments against Aristotle to the first case; to bodies of the same species that differ only in size. For these bodies the difference in size is directly translated into a difference in absolute weight and most—not all (see 4)—of the effects of the medium's resistance are the same. While for bodies of different species things are more complicated; they could differ in the three different ways enumerated above (see Fig.1). After his TE, Galileo will analyse bodies of different specific weights and bodies falling in different media simultaneously (see 3.1).

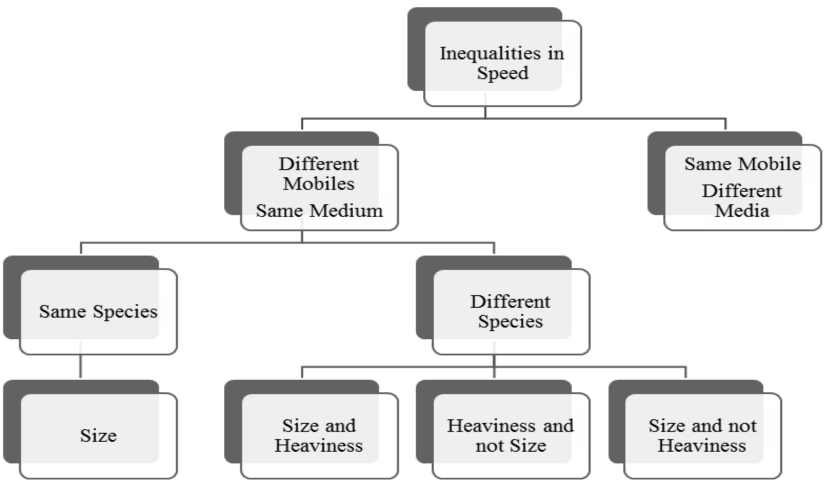

Fig.1:Galileo's *De Motu* analysis of the different ways inequalities in speed could come about

For bodies of the same species differing only in size (bottom left of Fig.1), Galileo starts by explicitly stating Aristotle's principle (i):

> Concerning those mobiles that are of *the same species* Aristotle has said, that the larger is moved faster [...] Aristotle wants mobiles of the *same genus* to observe between themselves in the speed of motion the ratio of the sizes that these mobiles have: and he says that very openly […], by affirming that a large piece of gold is carried more swiftly than a small one. (Galileo 1590: 15–16)

For bodies of the same species, principle (i) amounts to saying that the speed of a free-falling body is proportional to its volume or *absolute* weight. Galileo first dismisses this principle on empirical, or semi-empirical observations:

> How ridiculous this opinion is, is clearer than daylight: for who will ever believe that if, for example, [...] from a high tower, two stones, one being double the size of the other, were thrown at the same moment, that, when the smaller was at mid-tower, the larger would already have reached the ground?" (Galileo 1590: 16)

Then Galileo moves away from empirical examples to several arguments, the last one being his famous TE. Galileo starts by explaining his preference to appealing to non-empirical arguments in "seeking the causes of effects":

> [I]n order that we may always make more use of reasons than of examples (for we *are seeking the causes of effects, which are not reported by experience*), we will bring forth our way of thinking, whose confirmation will result in the downfall of Aristotle's opinion. (Galileo 1590: 16)

Galileo's entire thought process is somehow nested in two Archimedean analogies. The first concerns bodies floating on water, while the second concerns bodies heavier than water and thus sinking (see 3.1). Concerning the first Archimedean analogy, Galileo claims that the reason why bodies of the same species fall at the same speed is analogous to why a large beam and a small piece of wood float on water:

> We say, then, that mobiles of the same species (let those things be said to be of the same species that are constituted of the same material, such as lead or wood, etc.), though they may differ in size, are however moved with the same swiftness, and a larger stone does not go down more swiftly than a smaller one. Those who are surprised by this conclusion will also be surprised that a very large beam can float on water, just as well as a small piece of wood: for the reasoning is the same. (Galileo 1590: 16–17)

Before introducing his TE, Galileo first proposes a three steps argument[6] to explore this Archimedean analogy against Aristotle's principle (i):

In the first, Galileo invites us to think about the behaviour of a wooden beam and a stick of the same wood floating on the surface of the water. Galileo asks to imagine that the water's specific weight decreases to the point that it becomes lighter than the wood's. Then he asks, "who would ever say that the beam would go down first or more swiftly than the small piece of wood?" (Galileo 1590: 17).

In the second stage, Galileo reverses the strategy of the first. Instead of the medium's specific weight decreases, now the body's specific weight increases. He asks to imagine a volume of wax that is gradually filled with sand until the mixture's specific weight becomes bigger than the water's. Galileo then asks: "who would ever believe, if we took a particle of such wax, say one hundredth of it, either that it would not

[6] Cf. Palmieri (2005: 226–227) for a similar analysis

go down or that it would go down a hundred times more slowly than the totality of the wax?" (Galileo 1590: 17)

These analogies show Galileo's emphasis on specific weight rather than absolute weight when analysing the speed of free-falling bodies. This is especially reflected in the third stage, where he explores the analogy between a balance and bodies floating on water:

> And it will be possible to experience the same thing in the balance: for if very large, equal weights are placed on each side, and then to one of them something heavy, but only modestly so, is added, the heavier will then go down, but not any more swiftly than if the weights had been small. *And the same reasoning holds in water*: for the beam corresponds to one of the weights of the balance, while the other weight is represented by an amount of water as great in size as the size of the beam: if this amount of water weighs the same as the beam, then the beam will not go down; if the beam is made slightly heavier in such a way that it goes down, it will not go down more swiftly than a small piece of the same wood, which weighed the same as an [equally] small part of the water, and then was made slightly heavier. (Galileo 1590: 17)

This third step can be interpreted as an exploration of the analogy between the role of absolute weight on the balance[7] and the role of specific weight in the floatability of bodies on water:

In the first case, the equilibrium of the balance is broken if one adds a weight on one arm of the balance in equilibrium. Whatever the material of these two weights or the added weight, what matters is the difference between the absolute weight that is already on the scale and the added weight. The mobile "falls", so to speak, on an arm of the balance when an extra weight is added. This speed of fall does not depend on the initial body's absolute weight, but on the difference between the absolute weight of the initial body and that of the added body.

In the second case when analysing bodies sinking in water, this difference must be understood in terms of specific weight. It is when one changes the body's specific weight that the equilibrium, which existed between the body and the water, is broken, and the floating body then sinks. It sinks with the same speed, whatever its volume or absolute weight, a beam or a stick of wood. The speed of fall does not depend on the initial body's absolute weight, but on the difference between the specific weight of the floating body and the specific weight of the added body. Galileo will indeed defend at the end of his argumentative strategy that the speed of a free-falling body is proportional to the specific weight difference between the mobile and the medium (see 3.1). But first, Galileo will argue against Aristotle's principle (i) with his TE.

[7] Galileo will separate, in the *Discorsi*, from the idea that we could understand falling bodies by analogy to what happens in a balance, since bodies become weightless during their fall, a balance falling with a body cannot measure its weight. cf. Van Dyck 2006 for the analysis of the evolution of the role of the balance in Galileo's reasoning on free-fall.

2.1 *The TE in the* De Motu

Galileo introduces his TE as follows "[b]ut it is pleasing to confirm this by another argument". Its scenario is almost the same as that of the *Discorsi*, five decades later. The difference is in Galileo's justification of the following mediativity principle:

> And first, let the following be presupposed: namely, if there are two mobiles, one of which is moved faster than the other, the combination of the two is moved more slowly than that part which was moved faster than the other, but more swiftly than the remaining part, which, alone, was carried more slowly than the other. (Galileo 1590: 17–18)

In the *Discorsi*, Galileo justifies this supposition with the following theoretical axiom "each falling body acquires a definite speed fixed by nature, a velocity which cannot be increased or diminished except by the use of force" (Galileo 1638/1914: [107]). In the *De Motu*, this supposition is justified by appealing to two examples taken from empirical observations: the first concerns two mobiles ascending in water[8], while the second concerns two mobiles of different material falling in air:

> [I]f [...] two mobiles go down, one of which is carried more slowly than the other, as, for example, if one is wood, the other a bladder, which go down in air, the wood more swiftly than the bladder, we presuppose this: if they are combined, the combination will go down more slowly than the wood alone, but more swiftly than the bladder alone. For it is manifest that the swiftness of the wood will be retarded by the slowness of the bladder, while the slowness of the bladder will be accelerated by the speed of the wood; and similarly a certain motion intermediate between the slowness of the bladder and the swiftness of the wood will result. (Galileo 1590: 18)

Note that this justification may seem to be out of place in the context of the TE, since Galileo considers, as in the version in the *Discorsi*, two bodies of the same material. Nevertheless, this mediativity supposition is not weakened: Galileo, through these examples, seems to give it an empirical, or semi-empirical justification resulting from our daily experience.

Galileo then aims, with the following TE's scenario, at showing an inconsistency between this mediativity principle and Aristotle's principle (i):

> Let there be two mobiles *of the same species*, the larger a, and the smaller b; and, if it can be done, as our adversaries hold, let a be moved more swiftly than b. There are then two mobiles one of which is moved more swiftly than

[8] "As, for example, if we understand two mobiles, such as a piece of wax and an inflated bladder, both of which are carried upward from deep water, but the wax more slowly than the bladder, we ask that it be conceded, that if they are combined, the combination will go up more slowly than the bladder alone, but more swiftly than the wax alone. Indeed this is very clear: for who doubts that the slowness of the wax will be diminished by the speed of the bladder, and, on the other hand, that the speed of the bladder will be retarded by the slowness of the wax, and that a certain motion intermediate between the slowness of the wax and the speed of the bladder will result?" (Galileo 1590: 18).

> the other; hence, according to what has been presupposed, the combination of the two will be moved more slowly than a alone: but the combination of a and b is larger than a alone: hence, contrary to our adversaries' view, the larger mobile will be moved more slowly than the smaller; which would certainly be unsuitable. (Galileo 1590: 18)

That is in unfolding[9] the TE's scenario according to these two principles, we arrive at an absurd result describing the composite body falling, at the same time, both faster and slower than the larger body a. Which brings Galileo to conclude:

> Accordingly, let it be sufficiently confirmed that *there exists no cause*, per se, why mobiles of the *same species* should be moved with unequal speeds *but there certainly is one why they should be moved with equal speed*. But if there were some *accidental cause,* such as, for example, the shape of the mobile, it must not be classified amongst the causes per se. (Galileo 1590: 18)

This I submit is the function of the TE which is reflected in Galileo's own words in the *De Motu*: Galileo is isolating absolute weight in order to analyse it as a potential factor that could cause divergence in speed of free-falling bodies. He concludes, from his TE, that absolute weight could not be a causal factor and thus, contrary to Aristotle's principle (i), bodies of the same material do not fall proportionally to their absolute weight. Thus, bodies of the *same material* will fall with the same speed, if all "accidental" causes are accounted for. However, *the TE remains silent concerning the effects of other causal factors, in particular specific weight*.

I add that the TE's function will remain the same in the *Discorsi* (see 4), 5 decades later. The difference between these two occurrences of the same TE is to be found in the subsequent arguments that aimed at exploring *specific weight* as a potential causal factor, with *two conflicting conclusions*. To see that, let us compare how Galileo defended two incompatible theories of free-fall with two different argumentative strategies in 1590 and then in 1638.

3. *Specific weight in the* De Motu *(1590) and the* Discorsi *(1638): two argumentative strategies, two theories of free-fall*

In this section I aim at showing how Galileo defended two different theories of free-fall with different arguments that followed the same TE. I will show that this difference could be traced to Galileo's treatment of specific weight as a causal factor. I will first expose Galileo's *De Motu* second Archimedean analogy which led him to defend his early theory of free-fall: in void *all* bodies fall with a speed *proportional to*

[9] Cf. El Skaf and Imbert (2013) for a defence of unfolding as a general task of science involved in several tools (computer simulations, real experiments and TEs). Cf. El Skaf Rawad (2016) ch.7 for an account of how TE reveal and resolve inconsistencies through a common structure which involves mentally unfolding TEs' scenarios.

their specific weights. Second, I will expose how in the *Discorsi*, Galileo eliminated specific weight as a causal factor to defend his final theory of free-fall: in void, *all* bodies of *any* material, fall at the same speed.

3.1 De Motu*'s Archimedean analogy: specific weight is a causal factor*

The *De Motu* provides a very interesting manuscript to understand the evolution of Galileo's thought process, the limited function of his TE and his struggle with the causal role of specific weight, especially when compared with the *Discorsi's* argumentative strategy. In the *De Motu*, having eliminated absolute weight as a causal factor with the TE, by restricting its scenario to bodies of the same material, Galileo now wants to show that for bodies of different species, Aristotle's principle (i) is also false. First, Galileo—by building on the equality of speed for mobiles of the same species differing only in size—reduces his analysis of mobiles *of different species,* which differ in the three ways listed in Fig. 1, only to those differing "in heaviness and not in size". He argues that "if the ratio of the motions of those mobiles that differ only in heaviness and not in size is given, the ratios of those that differ in any other way are also given" (Galileo 1590: 19). Then Galileo tackles both principles simultaneously:

> And so, in order that we may find this ratio and, against Aristotle's way of thinking, show that in no way do mobiles observe the ratio of their heavinesses, *even if they are of different species,* [*i.e.* principle (i)] we will demonstrate things on which depends the answer not only to this investigation, but also to the investigation of the ratio of the motions of the same mobile in different media [*i.e.* principle (ii)]; and we will examine both questions simultaneously. (Galileo 1590: 19)

Galileo will examine both principle simultaneously with his second Archimedean analogy. Recall the first (see 2) Archimedean analogy concerned a large beam and a small piece of wood floating on water and Galileo used it to refute principle (i) for bodies of the same material. Galileo will build on the following second analogy to refute both principles and to defend his early theory of free-fall:

> [A]ll these things will easily be drawn from the following demonstration. I say, then, that a solid magnitude heavier than water is carried downward with as much force as that by which a quantity of water, having a size equal to the size of the same magnitude, is lighter than this magnitude." (Galileo 1590: 23)

Galileo provides several proofs of this latter claim (cf. Palmieri 2005: 229) and then concludes following this Archimedean analogy and contrary to principle (ii) that:

> [T]he same mobile going down in different media, observes in the swiftness of its motions, *the ratio to one another of the excesses of its own heaviness over the heavinesses of the media*: thus if the heaviness of the mobile is 8, but the heaviness of a size of one medium, equal to that of the mobile, is 6,

> then the swiftness of this body will be 2; if the heaviness of an amount of the other medium, equal to the size of the mobile, is 4, then the swiftness of the mobile, in this medium, will be 4. It is therefore evident that these swiftnesses will be to one another as 2 and 4; and not as the thicknesses or the heavinesses of the media, which is what Aristotle wanted, which are to one another as 6 and 4 (Galileo 1590: 24)

Galileo then applies the same reasoning to the fall of different bodies in the same medium, and concludes contrary to principle (i):

> Similarly the answer to the other question is evident: namely, what ratio the speeds of mobiles equal in size, but unequal in heaviness, observe with one another in the same medium. For the speeds of such mobiles will be to one another as the *excesses by which the heavinesses of the mobiles exceed the heaviness of the medium*: thus, for example, if two mobiles are equal in size, but unequal in heaviness, the heaviness of one being 8, and of the other 6, but the heaviness of an amount of the medium, equal in size to the size of one of the two mobiles, is 4, then the swiftness of the former mobile will be 4, and that of the latter will be 2. Hence these speeds will observe the ratio of 4 to 2; and not that which is between the heavinesses, namely 8 to 6. (Galileo 1590: 24)

Put differently, Galileo's early theory describes the speed of free-falling bodies as an Archimedean ratio (a subtraction), not geometric (a division) as Aristotle's wanted: The speed is not W/R (Weight/Resistance), but proportional to Wb—Wm (Wb and Wm being the specific weights of the body and the medium respectively)[10]. Thus, according to this early theory, in void where Wm = 0, mobiles fall proportionally to their specific weight:

> Thus, in a void also *a mobile will be moved in the same way as in a plenum*. For in a plenum a mobile is moved swiftly according to the excess of its own heaviness over the heaviness of the medium through which it is moved; and thus *in a void it will be moved according to the excess of its heaviness over the heaviness of the void:* since this is null, the excess of the heaviness of the mobile over the heaviness of the void will be the total heaviness of this same mobile; *thus it will be moved swiftly according to its own total heaviness.* (Galileo 1590: 32)

That is in the *De Motu,* Galileo defends that specific weight is a causal factor affecting speed, *even in void*. In addition, this theory is consistent with the TE since specific weight is a mediative property. That is combining in the TE's scenario two bodies of different specific weights results in a body whose specific weight lies between the specific weights of the two constituent bodies. Which means that—according to the mediativity principle, but also according to the *De Motu's* theory—the combined body should fall at an intermediate speed. To see this, consider Gendler's reconstructed argument which aims at revealing a contradiction between 3 premises; *i.e.* (1) speed is mediative, (2) absolute weight is additive (3) natural speed is directly proportional to absolute weight. This shows a contradiction since a "mediative property cannot

[10] Cf. Koyré (1960) and Van Dyck (2006) for a similar formula.

be directly proportional to one that is additive" (Gendler 1998, p.404). But we can rewrite the argument as follows without any contradiction: (1) speed is mediative, (2) specific weight is mediative (3) natural speed is directly proportional to specific weight. As we will see (3.2), in the *Discorsi* Galileo needed additional arguments to eliminate specific weight as a causal factor.

Finally, it should be noted that Galileo, immediately after defending the Archimedean ratios in plenum, notes that "a very great difficulty arises here: it will be found that these ratios are not observed by one who has made a test." However, without exploring this further, since he is convinced that "[i]t is necessary first to examine certain things which have not yet been inspected. For it is necessary, first, to see why natural motion is slower at the beginning." (Galileo 1590: 24)

3.2 Discorsi's *limiting case argument: specific weight is probably not a causal factor*

Five decades later, the same TE was reused by Galileo for the same purpose. However, the TE now constituted the first step of a more complex argumentative strategy which spans for 30 pages. Following the TE, Galileo will now propose two additional arguments, which will bring him to *eliminate specific weight as a causal factor* and to defend his final theory of free-fall: in void, *all* bodies fall at the same speed. This is how he argued. Following the TE, the second step consisted of a limiting case argument:

> SALV. [...] in a medium of quicksilver, gold not merely sinks to the bottom more rapidly than lead but it is the only substance that will descend at all; all other metals and stones rise to the surface and float. On the other hand the variation of speed in air between balls of gold, lead, copper, porphyry, and other heavy materials is so slight that in a fall of 100 cubits a ball of gold would surely not outstrip one of copper by as much as four fingers. *Having observed this I came to the conclusion that in a medium totally devoid of resistance all bodies would fall with the same speed.* (Galileo 1638/1914: [116])

It is thus this "observation", not the TE, that brought Galileo to the conclusion that in void, *all* bodies would fall at the same speed. Having observed that the variation of speed, of bodies of different specific weights, becomes less and less important with the ratification of the medium, we could extrapolate what will happen at the limit in a medium totally devoid of resistance:

> [...] if we find as a fact that the variation of speed among bodies of different specific gravities is less and less according as the medium becomes more and more yielding, and if finally in a medium of extreme tenuity, though not a perfect vacuum, we find that, in spite of great diversity of specific gravity [peso], the difference in speed is very small and almost inappreciable, then we are *justified in believing it highly probable* that in a vacuum all bodies would fall with the same speed. (Galileo 1638/1914: [117])

But, as it is made explicit by Galileo, we are justified in believing that in void *all* bodies fall at the same speed, only as "*highly probable*"[11]. In fact, this is the case since this limiting case argument is also consistent with the *De Motu* early theory: at the limit, and therefore in a vacuum, the differences in speed between two falling bodies with different specific weights could only be *small,* not null. As shown in Palmieri's diagrams (Fig.2), both Galilean theories predict divergences in the speed of falling bodies of different materials in plenum. In addition, both theories are consistent with this limiting case argument since they also predict that this divergence decreases with the ratification of the medium. However, in void, the two theories give two different predictions: in the diagram to the left, with the "restricted" *De Motu's* theory, when the resistance of the medium becomes null, there will always be a small difference in the speed of falling bodies of different material. In void, the sphere made of gold falls faster than the one made of gold + silver, since specific weight is a causal factor according to the *De Motu's* theory. While in the diagram on the right, with the "general" *Discorsi* theory, the speed of all falling bodies will be identical in void, since specific weight is no longer a causal factor.

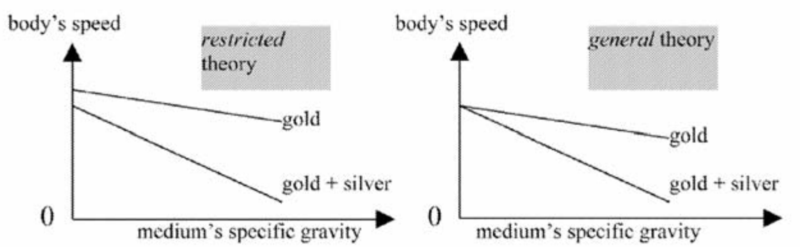

Fig.2: Inequalities in speed according to both theories (Palmieri 2005: 234)

Galileo needed one additional step in his argumentative strategy in order to pass from "highly probable" to "confirming" his theory of free-fall. Which will provide him with a way to choose between his early and final conflicting theories, that is to make a theoretical choice. Galileo will provide an argument which aims at eliminating specific weight as a causal factor affecting the speed of free-falling bodies in void.

3.3 Discorsi's *constant cause, constant effect argument or fall from small and high altitudes: specific weight is not a causal factor*

Galileo starts by setting up the stage for his analysis of different bodies falling from different altitudes. Salviati first raises and answers the following question:

[11] This is also explicit in Galileo's *Postils to Rocco* (ca. 1634–1635) where he also uses the same TE and arguments as in the *Discorsi* (cf. Palmieri 2005: 232–233).

> SALV. [...] Now, Simplicio, if we allow these two bodies [an inflated bladder and a mass of lead having the same size] to fall from a height of four or six cubits, by what distance do you imagine the lead will anticipate the bladder? You may be sure that the lead will not travel three times, or even twice, as swiftly as the bladder, although you would have made it move a thousand times as rapidly. (Galileo 1638/1914: [117])

To which Simplicio agrees, but adds that if they fall from a high altitude the difference will be bigger:

> SIMP. It may be as you say during the first four or six cubits of the fall; but after the motion has continued a long while, I believe that the lead will have left the bladder behind not only six out of twelve parts of the distance but even eight or ten. (Galileo 1638/1914: [117])

Which will provide Salviati with the opportunity to analyse this divergence in speed of fall from different altitudes, all the while confirming that specific weight could not be a causal factor:

> SALV. I quite agree with you and doubt not that, in very long distances, the lead might cover one hundred miles while the bladder was traversing one; but, my dear Simplicio, *this phenomenon* which you adduce against my proposition *is precisely the one which confirms it.* (Galileo 1638/1914: [117–118])

Galileo passes thus from "highly probable" following his limiting case argument, to "confirms" now. Here is how he argues with a *constant cause, constant effect argument*[12]:

> SALV. [...] Let me once more explain that the variation of speed observed in bodies of different specific gravities *is not caused by the difference of specific gravity* but depends upon external circumstances and, in particular, upon the *resistance of the medium, so that if this is removed all bodies would fall with the same velocity*; and this result *I deduce mainly* from the fact which you have just admitted and which is very true, namely, that, in the case of bodies which differ widely in [specific] weight, their velocities differ more and more as the spaces traversed increase, *something which would not occur if the effect depended upon differences of specific gravity.* For since these specific gravities remain *constant,* the ratio between the distances traversed ought to remain *constant* whereas the fact is that this ratio keeps on increasing as the motion continues (Galileo 1638/1914: [118])

That is, when observing two bodies of different specific weights free-falling from a small and a high altitude, we realize that from a small altitude the difference in speed is so small that is barely observable, while from a high altitude the difference in their speed increases as the spaces traversed increase. Since from *a constant cause we should get a constant effect*, differences in specific weights, which remains constant, should cause the same variation of speed from small and high altitudes. Having observed that this variation of speed is not constant, but increases during the fall, we could conclude that differences in specific weights cannot cause this variation of speed, which should be caused by external factors; *i.e.* the resistance of the medium. Thus in void,

[12] Cf. Koyré (1960: 213) for a similar analysis

when the medium's resistance is removed, all bodies would fall with the same speed.

But Simplicio remains unpersuaded that this difference in speed should be caused by the medium's resistance, in such a way that if removed, all bodies would fall at the same speed. He will thus question the reason as to why the *same* medium produces *different* effects with the increase of the altitude of fall. Since the medium does not change as well, it should also produce a constant effect:

> SIMP. Very well: but, *following your own line of argument*, if differences of weight in bodies of different specific gravities cannot produce a change in the ratio of their speeds, *on the ground that their specific gravities do not change,* how is it possible for the medium, *which also we suppose to remain constant*, to bring about any change in the ratio of these velocities? (Galileo 1638/1914: [118])

Which provides Galileo the opportunity to meet this "clever" objection by explaining how the effect of the medium's resistance increases with acceleration:

> SALV. […] There is […] an increase in the resistance of the medium, not on account of any change in its essential properties, but on account of the change in rapidity with which it must yield and give way laterally to the passage of the falling body which is being constantly accelerated. (Galileo 1638/1914: [119])

That is, the medium's resistance is treated differently in the *De Motu* and the *Discorsi*: In the latter, the medium not only makes the body lighter as in the *De Motu*, it also has a frictional effect, which keeps on increasing until the falling body reaches its terminal velocity: "the speed [of the falling body] reaches such a point and the resistance of the medium becomes so great that, balancing each other, they prevent any further acceleration and reduce the motion of the body to one which is uniform and which will thereafter maintain a constant value." (Galileo 1638/1914: [118]).

The effect of specific weight is also treated differently in the *De Motu* and the *Discorsi*, in plenum and in void. In the former, the young Galileo defended that speed of fall is proportional to the specific weight difference between the mobile and the medium, which brought him to conclude that in void, where the medium's specific weight is null, speed is proportional to the mobile's specific weight. While in the *Discorsi*, the difference in speed that we observe in plenum for two free-falling bodies, of different specific weights, does not translate to a difference in speed in void, since:

> [Specific] weight is the means employed by the falling body to open a path for itself and to push aside the parts of the medium, *something which does not happen in a vacuum* where, therefore, *no difference [in speed] is to be expected from a difference of specific gravity*. (Galileo 1638/1914: [118])

Put differently, while the *De Motu*'s theory could be written as follows $V \sim Wb - Wm$ (see 3.1), the *Discorsi*'s theory could be written as follows:

V = Vo [Wb – Wm]/Wb (Wb and Wm are as before the specific weights of the body and the medium, Vo is the speed in void)[13]. Thus in void where Wm = 0, all bodies fall at the same speed Vo.

Finally, Galileo will provide an empirical test: since measuring this variation in speed of two bodies falling from small heights was technically impossible at his time, and so "if there be a difference it will be inappreciable", Galileo will propose to substitute these observations by observations on pendulums with equal bobs made from different material. In these experiments Galileo could "repeat many times the fall through a small height" in such a way that they become "not only observable, but easily observable" (Galileo 1638/1914: [128]). But this, as Palmieri notes, is a different story.

4. *Ignoring the medium's resistance without assuming vacuum*

We could now answer the question asked in the introduction, why is the TE restricted to bodies of the same material, as follows: Galileo, in restricting his TE's scenario to bodies of the same material, was able to isolate and eliminate absolute weight as a causal factor and to postpone his analysis of specific weight and the medium's resistance. That is, Galileo in his TE only addressed principle (i), without making any reference to the effects of the medium's resistance, which is described in Aristotle's principle (ii). In this section I aim to analyse if Galileo was justified in ignoring the medium's resistance, *without assuming vacuum*. In fact, this assumption which is usually legitimate if the context were different, could not be explicitly made by Galileo: the TE appears in a larger discussion concerning the existence of vacuum and the possibility of motion in void, which makes any explicit assumption of vacuum inadmissible in the TE.[14]

Atkinson and Peijnenburg (2004) set out to analyse the speed (acceleration and terminal velocity) of fall of bodies in different situations: bodies of different material falling in plenum and in void, from the same altitude and different altitudes, from small and high altitudes, etc. This analysis, even it is irrelevant to and consistent with Galileo's TE as analysed here (since I defend that Galileo's TE is only refutational[15]), remains interesting in its own right: it shows the complexity of

[13] Cf. Koyré (1960) and Van Dyck (2006) for a similar formula.

[14] Indeed, assuming vacuum at this point in the TE could invite the Aristotelian to reject the TE on the ground that void is impossible. cf. El Skaf (2016) ch.7 for an analysis of how TEs could fail and El Skaf (2017) for an analysis of the notion of possibility at play in TEs.

[15] Which seems in line with Atkinson and Peijnenburg analysis as summarized in 2007: "As a destructive thought experiment, refuting the Aristotelian theory of falling bodies, we deem Galileo's thought experiment to be unparalleled, one of the best. But as a constructive thought experiment, claiming that all bodies fall at the same rate, it has a serious flaw. For it fails to make explicit a hidden assumption

taking into account all relevant causal factors—known (e.g. medium's resistance in plenum) or even unknown (e.g. inhomogeneous gravitational field of the earth, even in void) by Galileo—that could affect the speed of free-falling bodies.

Some interesting parts of this analysis, which are directly related to Norton's quote in the introduction concerning Galileo's "hidden" assumption 8a—*i.e.* speed of fall depends *only* on the body's weight –, are in fact explicitly addressed by Galileo in the *Discorsi*. This is first reflected in Galileo's choice of particulars involved in his TE's scenario—bodies made of the same material and have the same shape differing only in size—and second by Galileo's analysis of a small effect of the medium's resistance affecting even these particulars.

First, directly after the TE, Galileo underlines that:

> Aristotle declares that bodies of different weights, in the same medium, travel (in so far as their motion depends upon gravity) with speeds which are proportional to their weights; this he illustrates *by use of bodies in which it is possible to perceive the pure and unadulterated effect of gravity [i.e. absolute weight],* eliminating other considerations […] which are greatly dependent upon *the medium which modifies the single effect of gravity alone* (Galileo 1638/1914: [109]) (Galileo 1638/1914: [109])

Put differently, Galileo is making Norton's hidden assumption 8a *but without assuming vacuum*. By his choice of particulars Galileo is considering a situation, like Aristotle did, in which absolute weight is the only causal factor and it is possible to perceive its pure and unadulterated effect. But Galileo is not making this assumption to argue from his TE that *all* bodies fall at the same speed, as in Norton's TE-argument (Norton 1996: 341–343)—since even assuming 8a, bodies could fall proportionally to their specific weights as we have seen in (3.1) –, but to show that absolute weight could not be a causal factor, contrary to Aristotle's principle (i) or any other theory linking differences in speed to differences in absolute weight.

Second and more subtly, Galileo knew that even for these bodies, *most*, not all of the effects of the medium's resistance could be taken into account in his TE. Most, not all since one small effect of the medium's resistance remains disproportional for larger and smaller bodies. Indeed, just before the above quote, Galileo makes reference to this small effect when he claims that "[y]ou find, on making the experiment, that the larger outstrips the smaller by two finger-breadths" and then dismisses this difference on the account that Simplicio would "not hide behind these two fingers the ninety-nine cubits of Aristotle".

Finally and most importantly, at the end of his argumentative strategy Galileo comes back to this small effect and sets out "to explain how one and the same medium produces such different retardations in bodies *which are made of the same material and have the same shape, but dif-*

that is not always applicable, namely that the rate of fall of a body depends only on its weight, and on nothing else." (207)

fer only in size" (Galileo 1638/1914: [132]). For Galileo this explanation "requires a discussion more clever than" the previous explanations of the different effects of the medium's resistance. Galileo's solution lies in:

> [T]he roughness and porosity which are generally and almost necessarily found in the surfaces of solid bodies. […] in the motion of falling bodies these rugosities strike the surrounding fluid and retard the speed; and this they do so much *the more in proportion as the surface is larger, which is the case of small bodies as compared with greater*. (Galileo 1638/1914: [132])

That is, the medium affects disproportionally even the two falling mobiles involved in the TE's scenario. The medium's resistance is more important the bigger the mobile's surface to absolute weight ratio is. The medium thus affects less the speed of fall of the larger mobile than that of the smaller one, since the former have a smaller surface to absolute weight ratio than the latter (for which Galileo provides a geometrical proof, Galileo 1638/1914: [133–134]). The larger mobile will be less retarded by the medium and thus will have a greater speed. Which means that, in the context of the TE where Galileo is in no position to assume vacuum, the larger mobile falls faster than the smaller one. If we take this effect into account in the TE's scenario, then it is hard to see how even the destructive conclusion could be obtained. Galileo thus needed to ignore this small effect of the medium's resistance in order to refute Aristotle's principle (i).

If we don't ignore this effect of the medium's resistance, then how should we analyse the TE. One option, which rather complicates things, is to analyse how the two bodies are tied together: are they merely united or smelted together. This point has already been raised by Gendler (1998) and Atkinson and Peijnenburg (2004). In analysing Norton's hidden assumption 8a and Gendler's reconstructed argument, Atkinson and Peijnenburg correctly explain that if we take into account this small effect of the medium's resistance, then things get complicated, since "two lead spheres of different weights (and therefore with different volumes), will have different terminal velocities. If they are tied together side-by-side, the terminal velocity of the united system will lie between the terminal velocities of the constituents [... and Galileo is justified in refuting Aristotle's principle (i)]. If, on the other hand, the spheres are melted and recast as one sphere of weight equal to the sum of the weights of the two original spheres, then the terminal velocity of the united system will be greater than those of either of the constituents. The reason [as we saw Galileo was aware] is that the retarding viscous force is a function of both the velocity and of the surface area of the falling body. The smelted sphere falls more quickly than the united spheres because the surface of the former is smaller than the combined surfaces of the latter." (p. 123) In this latter case, Galileo is no longer able to refute Aristotle's principle (i), since the smelted body falls faster than its constituents. That is, the mediativity principle no longer applies for smelted bodies.

I submit that there is no need to complicate the TE's analysis: Galileo is in a position to ignore this small effect of the medium's resistance since the TE appears in a larger argumentative strategy in which Galileo comes back to this effect and explains it.

5. *Conclusion*

Let us summarize and conclude. In this paper I aimed at clarifying the reasons behind Galileo's restriction, in the TE's scenario and conclusion, to bodies made of the same material. This restriction turned out to be of central importance to understanding the function and limit of the TE. I retraced the history of this TE to its first occurrence in the *De Motu* and showed that the TE is only refutational; it aimed at refuting Aristotle's principle (i) by showing that absolute weight could not be a causal factor.

I then exposed how Galileo, following the same TE, defended two incompatible theories of free fall and I argued that both theories could be traced to Galileo's analysis of specific weight: following a hasty Archimedean analogy, the young Galileo maintained specific weight as a causal factor and defended an early theory of free-fall according to which speed is proportional to specific weight, even in void. Five decades later and with two new arguments, Galileo eliminated specific weight as a causal factor and defended his final theory of free-fall according to which in void, *all* bodies fall at the same speed.

I finally showed that Galileo, in the TE, needed to ignore one small effect of the medium's resistance affecting even the kind of particulars involved in the TE's scenario: bodies made of the same material and having the same shape, differing only in size. This effect either complicates the TE if it is taken into account, or Galileo is justified in ignoring it only when we analyse the TE as part of a general argumentative strategy in which Galileo comes back to this small effect and explains it.

In conclusion, we could draw out from this historical analysis at least the following two implications for the debate on TEs.

First contra Norton's "irrelevant particulars" and elimination thesis (see ft 1), in appraising TEs it seems crucial to analyse the function(s) of some of the details involved in their scenarios, instead of trying to eliminate them. Indeed, some particulars involved in a TE's scenario have a crucial function. In Galileo's TE, they permit to isolate the effect of absolute weight *without assuming vacuum*. Of course some particulars are irrelevant, for instance the two falling bodies could be yellow or blue, weight 8 and 4 kg or 12 and 6 kg, however they should be made of the same material and have the same shape, if not absolute weight could no longer be isolated as a causal factor. In addition, following the TE and Norton's quote in the introduction, the equality in speed only applies to "special cases", that is to the kinds of particulars involved in the TE's scenario for which we could ignore the effect of the medium's resistance.

Which is not the case for *any* two free-falling bodies, *even* of the same material. For instance, for bodies having a different shape, such as a nugget of gold and a leaf of gold (example given by Galileo), the medium's resistance could no longer be ignored without assuming vacuum.

Second contra Brown, it is clear that Galileo's TE could not, and even did not reveal, and a fortiori justify a law of nature—*i.e.* in void*, all* bodies fall at the same speed—platonically or otherwise. For the simple reason that following the TE, and even if we assume vacuum, we still don't know if bodies fall proportionally to their specific weight (1590) or not (1638). The TE, restricted to bodies of the same material having the same shape, allows Galileo to isolate and eliminate absolute weight as a causal factor, but remains silent concerning other causal factors, in particular specific weight (see 3). At most, the TE could lead to a weaker reading of the law; *i.e. all* bodies *of the same material* fall at the same speed. However, this conclusion follows if the medium's resistance is the only remaining causal factor (see answer to the last question below) and if we are justified in idealizing *all* of its effects, in such a way that we could say, following the TE, that a nugget of gold falls at the same speed than a leaf of gold, which amounts to assuming vacuum.

Finally, answers to the questions formulated in the introduction are found explicitly throughout the paper, let me restate them briefly here for clarity: What is the TE's function (or intended conclusion) for Galileo? To show that absolute weight is not a causal factor, thus refuting Aristotle's principle (i). What is its role in Galileo (1590 and 1638)'s argumentative strategies? To eliminate absolute weight as a causal factor, thus paving the way to analyse specific weight and the medium's resistance. What is the function of the particulars involved in its scenario? To isolate absolute weight in order to eliminate it as a causal factor. What are the idealisations involved? Void is not explicitly assumed, but one small effect of the medium's resistance is ignored. Are these idealisations justified? Yes, if we analyse the TE in the general strategy where this small effect is subsequently explained. Since vacuum could not be explicitly assumed in the TE and thus its scenario takes place in plenum, then how did Galileo take into account the multiple effects of the medium's resistance? Most of them were taken into account by Galileo's choice of particulars, one small effect was ignored but then later explained. In case we assume vacuum (for modern readers), what constructive conclusion could the TE lead to? At most, the TE could lead to the following: *in void*, all bodies *of the same material* fall at the same speed. Is this conclusion justified? Yes, if there are no remaining causal factors. But as shown in Atkinson and Peijnenburg (2004: 124–125) and unbeknown to Galileo, different causal factors could affect speed, even in void. For instance, the earth inhomogeneous gravitational field affects disproportionally the acceleration of bodies of the same material when they are dropped from different heights.

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