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Knowing what would happen: The epistemic strategies in Galileo's thought experiments

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ABSTRACT

While philosophers have subjected Galileo's classic thought experiments to critical analysis, they have tended to largely ignored the historical and intellectual context in which they were deployed, and the specific role they played in Galileo's overall vision of science. In this paper I investigate Galileo's use of thought experiments, by focusing on the epistemic and rhetorical strategies that he employed in attempting to answer the question of *how one can know what would happen in an imaginary scenario*. Here I argue we can find three different answers to this question in Galileo later dialogues, which reflect the changing meanings of 'experience' and 'knowledge' (*scientia*) in the early modern period. Once we recognise that Galileo's thought experiments sometimes drew on the power of memory and the explicit appeal to 'common experience', while at other times, they took the form of demonstrative arguments intended to have the status of *necessary truths*; and on still other occasions, they were extrapolations, or probable guesses, drawn from a carefully planned series of controlled experiments, it becomes evident that no single account of the epistemological relationship between thought experiment, experience and experiment can adequately capture the epistemic variety we find Galileo's use of imaginary scenarios. To this extent, we cannot neatly classify Galileo's use of thought experiments as either 'medieval' or 'early modern', but we should see them as indicative of the complex epistemological transformations of the early seventeenth century.

1. Introduction

Galileo is widely recognized as a masterful exponent of the use of thought experiment in science. His writings are replete with imaginary scenarios involving moving ships, falling stones and balls rolling down inclined planes. In 1969 Charles Schmitt noted, "the role of thought experiments" in Galileo's early work, "as well as the more general problem of their changing function as Galileo developed from youth to maturity and adage—is a very important one which should be dealt with in detail" (Schmitt, 1969, p. 87). Yet, in spite of the prominent role that thought experiments assumed in Galileo's writings, there has been relatively little detailed historical analysis of how they functioned in his science. Scholars have long recognised that thought experiments played an important rhetorical role in Galileo's writings. Michel Segré, for example, argues that while Galileo did perform many concrete experiments, he often preferred to present his reader with "much simpler, "ideal" experiments". In "presenting his science" to the reader, "Galileo put his trust more in thought experiments than in real ones" (Segré, 1980, p. 246). Yet the question of *how* Galileo attempted to persuade his reader of conclusions by means of the contemplation of imaginary scenarios is one that merits further attention. This paper attempts to address just this question, through an examination of the different epistemic strategies that Galileo employed in his use of thought experiments, particularly in his later dialogues.

Notwithstanding the important recent work of and Paolo Palmieri (2005) and Carla Rita Palmerino (2011), the general neglect of serious historical scholarship into Galileo's use of thought experiments can be sharply contrasted with the fact that

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many of them feature prominently in the now extensive philosophical literature on thought experiments. While philosophers have subjected many of Galileo's classic thought experiments to careful critical and logical analysis, they have tended to ignore the historical and intellectual context in which they were deployed, and the specific role they played in Galileo's overall vision of science (Adler, 2003; Atkinson, 2003; Atkinson & Peijnenburg, 2004; Brown, 1991; Gendler, 1998; Humphreys, 1993; Kuhn, 1977). This is a problem, because as many historians have noted, in spite of the popular image of Galileo as the progenitor of modern science, his *episteme* was in many respects foreign to that of the modern era. Indeed, as Nicholas Jardine has argued, many of his "basic assumptions about the proper ways to investigate and explain natural phenomena" were "entirely alien to our conception of science" (Jardine, 1991, p. 102). Here it is important to appreciate that Galileo's use of thought experiments needs to be situated within the context of the complex transformations that occurred in natural philosophy in the late sixteenth and early seventeenth centuries. It was during this period that the traditional meanings of 'experience' and 'knowledge' (*scientia*) would be contested and redefined.

Galileo's thought experiments were almost always presented in dialogical form, and often involved attempting to convince one of the protagonists in the dialogue of the truth of a proposition to which he was initially unwilling to give assent. The question of how Galileo attempted to persuade his readers of the certainty or probability of conclusions reached through the contemplation of imaginary scenarios, some of which could never be realized in practice, is therefore a question that brings to light both the epistemological and rhetorical aspects of Galileo's science. Indeed there is now an extensive literature that has demonstrated the complex ways, and the different contexts, in which these two aspects understood to be inextricably intertwined in the Renaissance and early modern natural period (Finocchiaro, 1980; Jardine, 1991; Moss, 1984, 1986; 1993; Vickers, 1983; Vickers & Struever, 1985; Wallace & Moss, 2003). As R. W. Serjeanston points out:

> The sixteenth and seventeenth centuries saw more self conscious theoretical reflection on how to discover and confirm the truths of nature than any period before or since; the same period also manifested a huge range of practical strategies by which investigators of the natural world set about demonstrating their findings and convincing their audiences of their claims… Inquiry into the early modern natural world, then, was inextricably bound up with the ways in which it was presented. Forms of proof and persuasion cannot be dissociated from the content of natural knowledge in the sixteenth and seventeenth centuries (Serjeanston, 2008, pp. 132, 175)

With this in mind, the problem I wish to examine, in Galileo's later writings, is: *how can we know what would happen in an imaginary scenario?* Framing the question in these terms brings to light the different ways in which Galileo understood the relationship between the traditional categories of 'experience' and 'knowledge', and in doing so provides us with a vantage point from which we can assess what, if anything, was novel or distinctive about Galileo's use of thought experiments. But equally importantly, by looking at the question of thought experiments from this perspective, we become aware of the different epistemic strategies employed by Galileo, which all have come to be identified as thought experiments. As Carla Rita Palmerino has rightly pointed out, the variety of different arguments "lumped together under the label 'thought experiments' were not regarded by Galileo as a unitary category" (Palmerino, 2011, p. 125). This contains an important clue to understanding Galileo's frequent invocation of imaginary scenarios in his writings. Here we do well to heed Kuhn's warning that "the category "thought experiment" is too broad and vague for epitome" (Kuhn, 1977, p. 241).

In this paper I distinguish three different epistemic and rhetorical strategies that Galileo used in generating knowledge about the world from imaginary scenarios. In the sections that follow, I illustrate each of these strategies through examples taken from Galileo two major dialogical works of the 1630s—*Dialogue Concerning the Two Chief World Systems* and the *Two New Sciences*. In the first class of thought experiments I consider, Galileo makes an appeal to 'common experience' or 'memory'. Here the reader is invited to consider what would happen in a given scenario, not by referring to any actually performed experiment or observation, but rather by appealing to the knowledge previously acquired through experience in course of everyday life. In doing so, Galileo remained close in spirit to the medieval Aristotelian tradition, though he often deployed such thought experiments to refute the conclusions reached by Aristotle.

The second class of thought experiments derives conclusions that are intended to have the status of *necessary truths*. Such thought experiments are much more like arguments, in the sense that they attempt to force the reader to arrive at a particular conclusion by exposing a contradiction or inconsistency in certain assumptions. In many respects these are much like *reductio ad absurdum* arguments, (though one need not be committed to the view that such thought experiments are simply picturesque forms of inductive or deductive inference). The demonstrative force of such thought experiments, for Galileo, lies in the fact that in executing them we feel compelled to reach the conclusion we do, because "it could not be otherwise". This class of thought experiment closely embodies the demonstrative ideal of science, which accorded with the traditional aim of *scientia* in the early 17th century—to arrive at necessary, and not merely contingent, truths about the world.

The third and final class of thought experiments I trace in Galileo's writings is perhaps the most interesting, because it involves explicit appeal to real experiments. Here Galileo argued that we can arrive at knowledge of what happens in the hypothetical scenario (such as free fall of bodies of different materials in a vacuum), not by imaginative speculation or reliance on previous experience, nor by demonstrative argument, but by observing what happens in series of cases which more and more closely approximate the ideal case. In this sense, Galileo advocated extrapolating from the concrete to the abstract, thus departing from the forms of reasoning he employed in his use of imaginary scenarios in other contexts. Before considering each of these epistemic strategies in more detail, it is worthwhile review the way in which historians and philosophers of science have attempted to make sense of Galileo's thought experiments by situating him in the context of medieval and early modern intellectual traditions.

2. The historiography of Galileo's thought experiments

Most historiographical approaches to Galileo's use of thought experiments have typically revolved around the question of whether, and to what extent, Galileo's use of thought experiments represented a decisive break with medieval natural philosophy, or represent a continuation of forms of argumentation that had their roots in medieval scholasticism. The different views expressed with regard to the place of thought experiment in the transition from medieval to early modern natural philosophy rehearse the familiar concerns of an earlier generation of historians of science, who grappled with the complex question of how best to understand the extent to which Galileo's science represented a continuation, or a departure from, the medieval tradition (Wallace, 1981; 1984). Of course framing the historical question in this way presents a number of familiar difficulties. It is not altogether clear how we should construe the discontinuity (or continuity) between the 'medieval' and 'early modern' natural philosophical and mixed mathematical traditions (Eastward, 1992). This disjunction has been variously construed in terms of a shift in epistemology, metaphysics, methodology, the motivation and aims of natural philosophy, the objects of investigation, as well as the reconfiguration of disciplinary boundaries and the emergence of new systems of patronage in the early modern era.

In spite of recent trends in historiography of early modern science, the discontinuity thesis has remained a powerful guiding concept in the philosophical accounts of thought experiment in Galileo's work. James McAllister, for example, has argued that during the course of the sixteenth and seventeenth centuries, thought experiments came to be used in the study of mechanics and natural philosophy, as exemplified in the work of thinkers like Stevin, Galileo, Huygens and Newton. According to McAllister, the rise of thought experiments in the 17th century marked a decisive break from the Aristotelian medieval tradition. "Whereas the experiment constituted a profoundly new methodological device, seventeenth century mechanics formulated an even more audacious concept: the thought experiment" (McAllister, 2005, p. 38). According to McAllister, Galileo's use of imaginary scenarios constituted a radical break from the evidential significance that Aristotelians accorded to natural occurrences: "For them, Galileo's thought experiments carried no weight" (McAllister, 2005, p. 51). In a similar vein, James Brown has argued, during the Scientific Revolution, "the thought experiment is the vehicle of the new way of doing science" (Brown, 1986, p. 1). On this account Galileo stands on the threshold of the modern era, as the progenitor of the new science.

Yet, such claims are difficult to square with the crucial role that thought experiments appear to have played in the medieval scholastic tradition. Hypothetical and counterfactual reasoning formed an indispensible part of medieval disputations on natural philosophy. One need only look to the 14th century writings of figures like Jean Buridan, Nicholas Oresme, Albert of Saxony, Thomas Bradwardine, and William of Heytsbery. Historians of medieval science like Edward Grant and Peter King have shown that thought experiments feature prominently in both the medieval *Obligationes* and the *Questiones* devoted to resolving problems of Aristotelian physics and cosmology (King, 1991; Grant, 2004). Indeed Grant goes so far as to say: "The most powerful tool medieval natural philosophers possessed was not empiricism as manifested by observation *per se*, but rather experience as adapted for use in thought experiments (*secundum imaginationem*)" (Grant, 2002, p. 141). While medieval philosophers typically made appeal to experiences "as if they had been personally performed or witnessed", in many cases, they were in fact thought experiments (Grant, 2004, p. 410). With this in mind, Peter King has drawn the following conclusion:

> The method of medieval science was thought experiment rather than actual experiment or testing … [revealing a] deep divergence between medieval *scientia* and modern scientific method… I would expect a closer look at Galileo would reveal his procedure was more "mediaeval" in this respect than has generally been acknowledged (King, 1991, p. 43, 56).

Like McAllister, King draws a sharp divide between the medieval and the early modern natural philosophy, but here he tentatively suggests that Galileo might be better identified with the earlier medieval tradition than the modern experimental tradition. Indeed, as Schmitt points out, in his early work *De Motu* Galileo saw "experiment", at least in the sense of a trial to test a proposition, as having "quite limited application for the investigation of problems of natural philosophy" (Schmitt, 1969, p. 85). Leaving aside problems concerning what we might see as constituting the "modern scientific method", King's remarks on Galileo's 'medieval' use of thought experiments provide an intriguing counterpoint to McAllister's views, but at the same time reinforce the discontinuity between the medieval and early modern approaches to natural philosophy.

Of course, the use of imaginary scenarios was by no means banished from natural philosophy with the rise of modern experimental science in the sixteenth and seventeenth centuries. Amos Funkenstein and, more recently, Carla Rita Palmerino have offered a more nuanced picture of the transformation that occurred with Galileo in the course of the 17th century. Both argue that thought experiments constitute an important part of medieval tradition, but take the view that in the early modern era thought experiments began to assume a different function in natural philosophy, than they had in the Middle Ages. According to Funkenstein, when medieval scholastics postulated imaginary scenarios, "the object was to show that what Aristotle may have thought was naturally impossible was indeed [logically] possible and intelligible" (Funkenstein, 1986, p. 177). The real purpose of contemplating counterfactual scenarios, such as the existence of a plurality of worlds or the existence of vacuum, was not to represent the world as it actually is, but to show that such an order of nature was possible, demonstrating God's *potentia absoluta*. By the seventeenth century, however, thought experiments had begun to take on a different function. As Funkenstein explains:

> Benedetti, Galileo, Huygens, Descartes, Pascal and Newton used their imaginary experiments in a way which differs *toto caelo* from their medieval predecessors not in discipline and vigor, but in their physical interpretation. Counterfactual states were imagined in the Middle Ages… But they were never conceived as commensurable to any of the factual states from which they were extrapolated…. For Galileo, the limiting case, even where it did not describe reality, was the constitutive element in its explanation. Then inertial motion of a rolling body, the free fall of a body in a vacuum, and the path of a projectile had to be assigned a definite, normative value (Funkenstein, 1986, pp. 177–8).

Here Funkenstein draws the conclusion that it was only with the dawning of the early modern era that natural philosophers "learned to assert the impossible as a limiting case of reality" (Funkenstein, 1986, p. 178). On this account Galileo is portrayed as representative of a decisive epistemological shift in the seventeenth century, in which counterfactual states, such as motion along a frictionless surface, could be treated as "as heuristic limiting cases to a series of phenomena, for example, the principle of inertia". By contrast: "Medieval schoolmen never did so; their counterfactual yet possible orders of nature were conceived as incommensurable with the actual structure of the universe" (Funkenstein, 1986, p. 11). Palmerino has also defended this reading: "Galileo explicitly rejected thought experiments that made appeal to divine omnipotence. In his view the only possible way to reason about imaginary scenarios was to explain them in conformity with the ordinary course of nature" (Palmerino, 2011, p. 103). Galileo staunchly rejected the medieval practice of considering imaginary worlds that God *could have* and *might have* created.

Yet medieval thinkers did on occasions use "ideal experiments" to serve other functions. As Funkenstein himself points out, during the fourteenth century, counterfactual scenarios were postulated, which, although not presented as limiting cases of reality, were relevant to the understanding of empirical phenomena

(Funkenstein, 1986, pp. 152–179). For example, in his discussion of impetus in his commentary on Aristotle's physics, John Buridan argued that "after leaving the arm the thrower, the projectile … would continue to be moved as long as the impetus remained stronger than the resistance, and would be of infinite duration were it not diminished and corrupted by a contrary force resisting it or by something inclining it to a contrary motion" (translated in Zupko, 2014).[1] We find something similar in Albert of Saxony's discussion of free fall in a vacuum: "we have never experienced the existence of a vacuum and do not really know what would happen if a vacuum did exist. Nevertheless we must inquire what might happen if it existed, for we see that natural beings undergo extraordinarily violent actions to prevent a vacuum" (translated in Grant, 1974, p. 339).[2] As these examples from Buridan and Albert make clear, medieval thinkers did sometimes employ idealizations as a method of philosophical inquiry into the nature of bodies themselves, though we should be too hasty in drawing the conclusion that in doing so, they anticipated Galileo's later work. As Palmerino has pointed out, whereas for Galileo, "a projectile thrown in the void would continue to move endlessly", for medieval defenders of impetus theory, the impetus imparted to a body is always corrupted by the contrary force of its heaviness (Palmerino, 2011, p. 107). Thus Buridan's claim that the motion of a projectile "would be of infinite duration were it not diminished and corrupted by a contrary force" is not necessarily in conflict with the view that all projectile motion "must come to end" (Palmerino, 2011, p. 107).[3]

The work of Palmerino and Funkenstin suggests that the relationship between the medieval and early modern thought experiments is more complicated than has often been assumed. Here it is worth noting that some of Galileo's thought experiments were simply adapted from, and in some cases borrowed directly form, classical medieval sources. Yet, while medieval philosophers often used such imaginary scenarios to establish the validity of propositions that were broadly keeping within an Aristotelian framework that distinguished between natural and violent motion, "Galileo consciously used a traditional way of arguing in order to build up his non-traditional conclusions" (Palmerino, 2011, p. 101). This critical use of thought experiments by Galileo has also been commented on by Schmitt, who noted that in his early manuscripts, Galileo was inclined to use thought experiments as a means of exposing the hidden absurdities in Aristotelian natural philosophy (Schmitt, 1969, p. 111).

The target of my attention in this paper is not on the *ends* to which Galileo put thought experiments, but rather on the *epistemic strategies* he employed in the contemplation of imaginary scenarios. Much of the recent literature on thought experiments has focused on their *aims*, and to this extent, there has been a tendency among certain authors to treat "thought experiment as a source of evidence about the world" (McAllister, 2004, p. 1170). Yet thought experiments are not in themselves sources of knowledge. Rather, in considering an imaginary scenario, the reader is called upon to draw upon other sources of knowledge. To this end, the epistemological problem I wish to examine, in examining Galileo's writings, is *how we know what would happen in an imaginary scenario*. As we shall see, there are three quite distinct answers to this question to be found in Galileo's writings.

3. The appeal to common experience and memory

The first class of imaginary scenarios that I wish to consider here is best illustrated through one of Galileo's famous thought experiments in the Second Day of the *Dialogue Concerning the Two Chief World Systems*. Here Salviati asks his interlocutors to consider a scenario inside the cabin of a stationary ship in which one can observe all manner of motions: fish swimming in a bowl, flies and butterflies flying about the cabin, a bottle hanging from a chord attached to the ceiling, the force required to throw an object to nearby a friend, and the distance one can cover in jumping in all directions with feet together. If one now considers the case of observing these same effects aboard a moving ship, Galileo maintains that we would observe no discernable change in their motions, "so long as the motion is uniform and not fluctuating this way and that". As Salviati explains:

> SALVIATI: You will discover not the least change in all the effects named, nor could you tell from any of them whether the ship was moving or standing still. In jumping, you will pass on the floor the same spaces as before, nor will you make larger jumps toward the stern than towards the prow even though the ship is moving quite rapidly, despite the fact that during the time that you are in the air the floor under you will be going in a direction opposite to your jump. In throwing something to your companion, you will need no more force to get it to him whether he is in the direction of the bow or the stern, with yourself situated opposite…
>
> SAGREDO: Although *it did not occur to me to put these observations to the test* when I was voyaging, *I am sure that they would take place in the way you describe*. Indeed, I remember having often found myself in my cabin wondering whether the ship was moving or standing still; and sometimes at a whim, I have supposed it going one way when its motion was the opposite (Galilei, [1632] 1953, pp. 186–8).

There is no evidence that Galileo ever specifically carried out an experiment like the one he describes here. But whether or not this is the case, it is clear that Salviati has no recourse to an actual experiment he had performed, but calls upon Sagredo to draw upon his experience and memory to corroborate this account. Indeed, it is these considerations that ultimately convince Sagredo that the phenomena "would take place in the way you describe". We may note with some irony that nearly five decades earlier, in the *Episteolarum astronomicarum*, Tycho Brahe invoked a similar thought experiment with the aim of convincing the reader of the opposite conclusion. In his defence of the stationary earth, Tycho argued that "a missile hurled upwards from a ship" would not "fall to the same place if the ship is moving as if it remained motionless", as some supposed, but instead "the swifter the ship advances, the more differences will be discovered" (translated in Overmann, 1975, p. 14). Actual recorded observations appear to have played no part in these discussions, though as we shall see in the next section some Aristotelians did respond to Galileo by referring to observational reports of falling stones on ships (Shea, 1972, p. 156; Grant, 1984, pp. 36–42).

The concept of experience invoked here by Galileo, and the explicit reliance on memory as a source of knowledge, played a pivotal role in sixteenth century natural philosophy. In 1591 Francesco Buonamici, who was a professor at Pisa during Galileo's student days, expressed this view: "Great is the power of experience, which arises from the memory of things, which sense time and again supplies; for indeed memory comes from repeated sensation. Many memories of the same thing grant the means of

[1] The original reference cited by Zupko is: Jean Buridan, Subtilissimae Quaestiones super octo Physicorum libros Aristotelis, Paris, 1509. Reprinted as Kommentar zur Aristotelischen Physik, Frankfurt a. M.: Minerva, 1964. XII.9: 73ra.

[2] The original reference cited by Grant is: Albert of Saxony, *Questions on the Eight Books of the Physics of Aristotle*, Book IV, Question 12.

[3] I thank the anonymous referees for making this point clear.

one experience" (translated in Schmitt, 1969, pp. 90–1).[4] This construal of experience persisted well into the 17th century—"a scientific 'experience", as Dear explains, "was not an 'experiment' in the sense of a historically reported experimental event. Instead it was a statement about the world that, although was known to be true thanks to the senses, did not rest on historically specifiable instances" (Dear, 1995, pp. 13–4). Only in the 17th century did "singular, contrived events became generally used as foundational elements in making natural knowledge" (Dear, 1995, p. 13).

Galileo's reliance on this form of everyday experience was typical of his early unpublished manuscripts. To this extent, Galileo frequently uses expressions like "experience teaches us" or "experience shows us" to refer to "experiences which he has previously gained" and were perfectly consonant with ordinary events, but which were not reported in the sense of a witnessed singular historical event.[5] This "commonsense reliance on daily experience" and memory and was in fact central to the scholastic tradition, and has its origins in Aristotle's *Posterior Analytics*: "From perception there comes memory… and from memory (when it occurs often in connection with the same thing), experience; for memories that are many in number form a single experience (translated in Barnes, 1975, p. 81).[6] Experiences, as construed in the Aristotelian tradition, Dear explains, were "usually constituted as statements of *how things happen* in nature, not as statements of *how things had happened* on a particular occasion" (Dear, 1995, p. 125).[7]

In this qualified sense, one might say that Galileo's frequent appeals to 'commonsense experience' in his writings marked a continuation of the medieval intellectual tradition. When medieval natural philosophers quoted the maxim: "There is nothing in the mind, which was not first in the senses", it is important to understand, this typically did not imply an appeal to direct observation or experiment. As Murdoch explains, the empiricist epistemology of the 14th century was not based on an overriding "concern about testing or matching its results with nature", or "the deliberate subjection of nature to searching questions" and "active interrogation", but rather, on "imaginative constructs", as exemplified in the frequently occurring phrase "*secundum imaginationem*" (Murdoch, 1982, p. 174). Echoing this view, Edward Grant has argued that medieval empiricism was grounded in "commonsense reliance on daily experience", as "adapted for use in thought experiments", which can be "contrasted with the 17th century approach in which the idea of *experiment* takes hold" (Grant, 2002, p. 141). We find numerous examples of this kind in the *Questiones* of medieval scholars like Albertus Magnus, Jean Buridan, Nicholas Oresme, and Roger Bacon. As Grant (2004) and King (1991) have shown, such authors routinely appealed to imaginary scenarios, involving windmills, canonical lances, and falling bodies, which they construed as experience. Many of Galileo's thought experiments were intended to subject Aristotle's theory of motion to criticism "for being in contradiction with everyday experience" (Palmerino, 2011, p. 106), yet, in invoking "everyday experience", Galileo was drawing on the same source of knowledge that his medieval predecessors had used in reaching their conclusions.

In some instances, the appeal to everyday experience as a source of knowledge could be made even when the imaginary scenario being contemplated was not immediately apparent from everyday experience. In such cases, the thought experimenter could draw conclusions as to what would happen in the imagined scenario on the basis of an *analogy* with phenomena familiar to everyday experience. This is evident, for example, in certain thought experiments we find in Galileo's writings, which were directly taken or adapted from medieval sources. A clear example of this can be seen in the fourteenth century discussions by Albert of Saxony and Nicholas Oresme, concerning what would happen if a stone reached its natural place at the centre of the universe, coinciding with the centre of the earth. In his *Le livre du ciel et du monde*, Oresme provided the following account:

> For if an opening were made from here to the centre of the earth and beyond and a heavy object fell though this opening or hole, upon reaching the centre it would pass beyond the begin to go upward be means of this accidental and acquired property [of impetus]; then it would fall back again and come and go several times just as we can observe in the case of a heavy object hanging from a beam by a long chord (Oresme, 1968 [c. 1377], p. 145).

This thought experiment featured prominently in 16th century discussions of upward and downward motions of heavy bodies, appearing in the writings of Eramsus of Rotterdam, Francesco Maurolico, Alessandro Piccolomini and Francesco Buonamici, who presented an in depth treatment of this scenario in chapter 44 of the second book of his *De Motu libri X* (Palmerino, 2011, pp. 107–8). It also appears on more than one occasion in Galileo's *Dialogue Concerning the Two Chief World Systems* (Galileo, [1632] 1953, pp. 135–6, 236). Galileo's discussion of this scenario in Day Two of the *Dialogue*, in which Salviati asks Simplicio to consider a cannon ball dropped into a hole that passes through the centre of the earth:

> SALVIATI: Having arrived at the centre is it your belief that it would pass beyond, or that it would immediately stop its motion there?
>
> SIMPLICIO: I think it would keep going a long way (Galilei, [1632] 1953, p. 236).

In the passage that follows, Galileo presents his reasons for holding the view that after passing the centre of the earth, a heavy body would continue to ascend. While the conclusion Galileo reaches, based on his understanding of pendular motion, is somewhat different from that adduced by Oresme, like Oresme, Galileo draws on the analogy with the pendulum in support of his contention. While of course, we have no direct experience of heavy bodies passing through the centre of the earth, one may draw an analogy with things with which we are familiar. Here Galileo presents the following analogy to the motion along a curved inclined plane and that of a pendulum:

> SALVIATI: For what is said thus about motion through the centre is also seen up here by us. For the internal impetus of a heavy body falling along an inclined plane which is bent at the bottom and deflected upward will carry the body upward also, without interrupting its motion at all. A ball of lead hanging from a

[4] The original reference cited by Schmitt is: Francesco Buonamici, *De Motu libri X quibis generalia naturalis philosophiae principia summo studio collecta continentur*, Florence, 1591.

[5] According to Schmitt, in his early writings, Galileo reserves the term '*periculum*' for a trial in which "one consciously devises a specific experimental or observational situation to resolve a particular difficulty" (Schmitt, 1969, p. 117). Galileo expresses a lack of confidence in the results of such trials.

[6] The original reference cited by Barnes is: Aristotle, *Posterior Analytics*, II, 19 100a3-9.

[7] As an aside, we may note that something very close to this idea experience can be found in Helmholtz's analysis of the origins of the Euclidean spatial intuition in 1876. Helmholtz did not hold the form of spatial intuition to be "a transcendental form given before experience" as did Kant. Nor did he believe it was established "by any carefully executed systems of exact measurement". Instead it had emerged through "a succession of every day experiences" in dealing with bodies of various sizes, and thus constituted a form of "knowledge *empirically gained by the aggregation and reinforcement of similar recurrent impressions in memory*" (Helmholtz, 1876, p. 320).

> thread and moved from the perpendicular descends spontaneously, drawn by its internal tendency, without pausing to rest it goes past the lowest point and without any supervening power it moves upward (Galilei, 1953 [1632], p. 236).

As Palmerino makes clear, Galileo's purpose in considering these examples is to defend the radical claim that the "principle that makes heavy bodies move upward … is no less internal and natural than those which moves them downward" (Palmerino, 2011, p. 235). It is important to recognise that, in contrast with Oresme and Buridan, Galileo's aim was to attack the Aristotelian distinction between natural and violent motion. However, much like his medieval predecessors, Galileo did not base his conclusions—at least in the specific example presented here—on results obtained by carefully performed experiments. Rather, he relied on analogical reasoning drawing on his ordinary experience of balls falling down curved inclined planes and the simple motion of a swinging pendulum. While it is true that Galileo did perform experiments with the inclined plane and the pendulum in support of his other quantitative claims, as Dear points out, in many instances throughout his writings, Galileo "did not provide narratives of what he had done and seen; instead he told his reader *what happens*". To this extent his appeal to everyday experience in support of his conclusions was effectively "tantamount to the invocation of thought experiments" (Dear, 1995, p. 126).

4. Thought experiments as demonstrative arguments

We should not get the impression from the preceding section that Galileo only ever invoked imaginary scenarios in situations where the conclusions reached were immediately apparent from, or based on analogies drawn from, everyday experience. In his later writings of the 1630s, Galileo attempted to use such imaginary scenarios as a form of demonstrative argument. Here we need to understand that the task of natural philosophy was widely understood by many of Galileo's contemporaries to consist in establishing *necessary* truths, not merely *contingent* truths. As Dear explains, "'experience' itself was incapable of explaining the necessity of these things to which it afforded witness" (Dear, 1995, pp. 11–2). Observations of natural phenomena could show that something *is the case*—however, they could not demonstrate that it *must* be the case. As Marta Fehér has argued, Galileo embraced a conception of knowledge, according to which the "goal of scientific inquiry is to seek *necessary* truths, which convey that which could not be otherwise" (Fehér, 1995, p. 29). Barry Gower makes a similar point in describing the demonstrative ideal of science: "Any science—*scientia*—must yield knowledge of … truths which are both universal and necessary, and such knowledge—philosophical knowledge—can only be arrived at by demonstration" (Gower, 1997, p. 24). This demonstrative ideal of knowledge was perhaps most clearly exemplified in the deductive formal structure of the mixed mathematical sciences in the Archimedean tradition.

In its most powerful form, a thought experiment, or imaginary scenario, could deliver such knowledge. Perhaps the clearest example of this can be found in Galileo's famous thought experiment designed to disprove the Aristotelian idea that heavier bodies fall faster than lighter ones. In the *Two New Sciences*, Salviati casts serious doubt on whether "Aristotle ever tested whether it is true that two stones, one ten times as heavy as the other, both released from the same instant to fall from a height" fall at such different speeds, such that the heavier one will arrive at the ground well before the lighter one. (Galilei, 1974 [1638], p. 66). Here Salviati attempts to persuade Simplicio that Aristotle's claim to have observed heavier objects fall faster than lighter ones simply cannot be right, as performing the experiment demonstrates quite the contrary. Indeed, it was possible to arrive at this fundamental truth *independently of experiment*:

> SALVIATI: But without other experiences, by a short and *conclusive demonstration, we can prove clearly* that it is not true that a heavier moveable is moved more swiftly than another, less heavy, [provided] these being of the same material… But tell me Simplicio, whether you assume that for every heavy falling body there is a speed determined by nature such that this cannot be increased or diminished except by the use of force or opposing some impediment to it.
>
> SIMPLICIO: There can be no doubt that a given moveable in a given medium has an established speed determined by nature, which cannot be increased except by conferring on it some new impetus, or diminished save by some impediment that retards it.
>
> SALVIATI: Then if we had two moveables whose natural speeds were unequal, it is evident that were we to connect the slower to the faster, the latter would be partly retarded by the slower, and this would be partly speeded up by the faster. Do you not agree with me in this opinion?
>
> SIMPLICIO: In seems to me this would undoubtedly follow.
>
> SALVIATI: But if this is so, and if it is also true that a large stone moves with eight degrees of speed, for example, and a smaller one with four [degrees], then joining both together, their composite will be moved with a speed less than eight degrees. But the two stones together make a larger stone than the first one which was moved with eight degrees of speed; therefore this greater stone is moved less swiftly than the lesser one. But this is contrary to your supposition. You see how, from the supposition that the heavier body is moved more swiftly than the less heavy, I conclude that the heavier moves less swiftly (Galilei, 1974 [1638], pp. 66–7 emphasis added).

After an extended discussion, Sagredo concedes that Salviati's argument has "clearly demonstrated that it is not true that unequally heavy bodies, moved in the same medium, have speeds proportional to their weights, but rather have equal [speeds]" provided we assume they are "of the same material (or rather of the same specific gravity)" (Galilei, 1974 [1638], pp. 71–2). This last caveat concerning bodies of the same substance or the same specific gravity is often overlooked, and we will return to this point later. But for the sake of our present discussion, what is important is that in the dialogue Salviati traps Simplicio in a putative contradiction. Simplicio finds himself compelled to acknowledge that the heavier of the two objects cannot fall both faster and slower than the composite body of a heavier and a lighter body, and thus the commitment to the Aristotelian view leads to a paradoxical state of affairs.

This was a method of argumentation that Galileo frequently employed. It its most general form, Galileo often posited an imaginary scenario that was designed to expose the hidden paradoxes, contradictions or inconsistencies, he saw to be implicit in Aristotle's conceptual framework. As Gendler puts it, by contemplating the imaginary scenario, Simplicio (the Aristotelian) becomes aware of "the inadequacy of his conceptual framework for dealing with phenomena which—through the contemplation of this imaginary case—he comes to recognize as always having been part of his world" (Gendler, 1998, p. 412). Another classic example of this strategy, discussed by Kuhn, is found in Galileo's thought experiment in which one compares the speed of a ball falling down a perfectly vertical plane with one falling down and inclined plane

(Kuhn, 1977). Here the protagonists of Galileo's dialogue find themselves caught in a conceptual muddle, in attempting to state unequivocally which of the two balls falls faster. The ensuing dialogue exposes the hidden ambiguity in the meaning of Aristotle's concepts of 'faster than' and 'slower than', before Salviati effectively resolves the issue by recourse to the concept of instantaneous velocity (Galilei, 1953 [1632], pp. 23–4). One might also see a similar form of argument at work in Simon Steven's famous thought experiment involving the 'wreath of spheres', which was intended to demonstrate the law of equilibrium. Here Stevin argued that the violation of this law, in the scenario considered, would result in perpetual motion, which was rejected *a limine*.

I am not claiming here that Galileo's thought experiment constitutes a valid logical 'proof' for his conclusion that speed is not proportional to weight. There is now an extensive philosophical literature that reveals how Galileo's thought experiment rests on hidden assumptions, which fail to establish the conclusion it is supposed to demonstrate (Irvine, 1991; Schrenk, 2004; Atkinson & Peijnenburg, 2004). Yet, it is evident, than in presenting this argument, Galileo certainly intended to convince his reader of this conclusion by a different rhetorical means than simple appeal to everyday experience. The thought experiment is an attempt to persuade the reader that the conclusion reached is not only true, but *necessarily true*. As Peter Dear has explained, the aim of such thought experiments was to "*create the conviction of truth*, of an untried outcome" (Dear, 1995, p. 62). These kind of thought experiments, carried a certain "demonstrative force", to use Gendler's phrase, that was unmatched by simple reliance on experience. Thus, in contrast to the view recently expressed by scholars such as David Atkinson, for Galileo and for many of his contemporaries, thought experiments of this kind were, or could be, more compelling that actual ones.

Here I wish to avoid the question, which has the subject of much philosophical debate and disagreement, of whether thought experiments of this kind are nothing more than disguised logical arguments, which employ standard forms of inductive or deductive inference (Arthur, 1999; Bishop, 1998; Brown, 1991; Gendler, 1998; Norton, 1996). We need not take a principled stance on this question here, though it is worth noting that assumptions that serve as the premises in the reconstructed argument often emerge and are revised in the course of contemplating an imaginary scenario (Camilleri, 2014). Indeed in Galileo's dialogues, this often takes several pages of exposition, in which the interlocutors engage in lively discussion about the presuppositions, before eventually reaching agreement. What is distinctive about such thought experiments, from a historical perspective, is that they were designed to expose the contradictions or paradoxes that appear to follow from certain intuitively held assumptions, thus compelling the reader to revise these assumptions. For this reason, such thought experiments can often be reconstructed as *reductio ad absurdum* arguments. This constitutes a quite different strategy than we find the previous class of thought experiments, which relied simply on familiarity with the phenomena, or previously acquired experience. While it is true that Galileo still called upon the reader to draw on previous experience, the structure and form of the thought experiment went beyond mere recollection or analogy, and was designed to reveal the conceptual incoherence, or better still, the impossibility of certain assumptions, that had initially seemed intuitively obvious.

We find a further example of this kind of thought experiment in another section of the *Two New Sciences*. We saw earlier that in the *Dialogue Concerning Two Chief World Systems*, how Galileo appealed to everyday experience, in invoking the scenario on board a moving ship, in defence of his belief in the relativity of motion. Galileo revisited this scenario, in an effort to counter the response of contemporary Aristotelian, who had simply rejected this claim. In responding to Galileo, Aristotelian natural philosophers did sometimes appeal to actual eyewitness accounts of stones dropped from the top of ships' masts. Such accounts claimed that while aboard a moving ship, stones dropped form a great height often fell overboard, not on to the deck below (Shea, 1972, p. 156; Grant, 1984, pp. 36–42).

Galileo deals with this issue in 'Day Two' of his *Dialogue Concerning Two Chief World Systems* (Galilei, 1953 [1632], pp. 141–4). In the dialogue, Salviati takes issue with the Aristotelian claim that a stone dropped from the top of a mast of a moving ship would land some distance from the base of the mast, notwithstanding the effects of wind and air resistance. Here Salviati accuses Simplicio of never having performed the experiment himself, and of relying on the faulty testimony of 'authorities' who claimed to have seen it happen. Salviati remains resolute in his belief that "anyone who does will find that the experiment shows exactly the opposite of what is written" (Galilei, 1953 [1632], p. 144). Yet Simplicio here points out that Salviati's claim that the Aristotelians are in error is no less dubious than that of the Aristotelians who claim to have witnessed the experiment (Galilei, 1953 [1632], pp. 141–4).

> SIMPLICIO: So you have not made a hundred tests or even one? And yet you so freely declare it to be certain? I shall retain my incredulity, and my own confidence that the experiment has been made by the most important authors who make use of it, and that it shows what they say it does.
>
> SALVIATI: Without experiment, I am sure that the effect will happen as I tell you *because it must happen that way*. And I might add that you yourself already know that *it cannot happen otherwise* no matter how you may pretend not to know it" (Galilei, 1953 [1632], pp. 145 emphasis added).

Here Galileo employs the rhetoric of the demonstrative ideal, in turning from reports of actual experiments, which he takes to be inconclusive, to a thought experiment, which, he insists, conclusively establishes the necessity of his claim. Salviati now asks Simplicio to consider three scenarios: a ball rolling up a frictionless inclined plane, a ball rolling down a declined plane, and a ball rolling along a perfectly horizontal plane. In the first case, Simplicio agrees the ball would continually accelerate as it fell, and in the second case, it would decelerate. But he now realizes that in the third limiting case, a body *must* continue to move at constant velocity (neither accelerating nor decelerating), provided it encounters no resistance and has been already set in motion. Simplicio thus in effect assents to the proposition that a stone moving horizontally to the earth (e.g. aboard a moving ship), would continue to move at constant velocity, provided it is not impeded. After much further discussion of what keeps a body moving once it is set in motion, the protagonists concede that the experiments purportedly carried out with stones falling aboard a moving ship in fact prove nothing. This argumentative strategy undertaken by Galileo might strike the reader as falling short of the goal of demonstrating the *necessary truth* of the proposition, but the salient point in recounting this exchange is that here Galileo attempts to settle the question of 'what would happen' by recourse to a thought experiment, which takes the rhetorical form of a demonstrative argument. This is what Jean Dietz Moss has called the "rhetoric of proof" in Galileo's dialogues (Moss, 1986; 1984).

5. Thought experiments as extrapolations from experiment

We now turn our attention to the third and final class of thought experiments. Here Galileo appeals neither to everyday experience, nor to demonstrative argument in support of his conclusions. Instead, Galileo suggests we must carry out a series of experimental observations to settle the issue of what happens in an imaginary scenario. While this might, at first glance, appear paradoxical, it depends on the extrapolative method. To bring this to light, we need to first introduce a fundamental issue, which preoccupied Galileo from his earliest days in considering the motion.

As Noretta Koertge has argued, the key problem that confronted Galileo was the problem of accidents, such as friction, or resistance, which "hide and obscure the essence of phenomena, so that it is impossible for the naïve observer to discover them through simple experiences". Concrete instances of free fall, such as in the case of a feather and a canon ball, will involve impediments such as friction and air resistance, which must be abstracted away if we are to attain a knowledge of the laws of falling bodies. "Accidents", as Keortge puts it, "not only impede and hinder the motion of falling bodies, they also interfere with our discovering and knowing the laws of motion" (Koertge, 1977, p. 392). In his early manuscript *De Motu*, written around 1590, Galileo drew attention to this issue, in his discussion of motion down inclined planes:

> [T]his proof must be understood on the assumption that there is no accidental resistance (occasioned by the roughness of the moving body or of the inclined plane, or by the shape of the body). We must assume that the plane is, as to speak, incorporeal, or, at least, that it is very carefully smoothed and perfectly hard… [O]ur demonstrations, as we also said above, must be understood of bodies free from all external resistance. But since it is perhaps impossible to find such bodies in the realm of matter, one who performs an experiment on the subject should not be surprised if the experiment fails (Galilei, 1960, pp. 37–8).

In his discussion of the phenomenon of free fall, Galileo was forced to consider the imaginary scenario of a body moving in a space free of all resistance and impediments. Here McAllister argues that Galileo left behind the world of sense experience and instead made explicit use of a thought experiment:

> Thought experiments [for Galileo] represent a continuation of the process of polishing and smoothing, until—to speak figuratively—the entire, imperfect physical apparatus of the experiment is smoothed out of existence. With the abstract experimental apparatus that remains, we can at last be certain that accidents will no longer obstruct our view of the phenomenon. If the phenomenon is so subtle that no concrete occurrence can be produced in which the phenomenon is displayed in accident-free form, the phenomenon may be displayed only in an abstract occurrence: that produced in a thought experiment. This view explains why Galileo, in the case of some phenomena, withdrew from the sphere of sense data and sought knowledge about the world in thought experiment rather than in concrete experiment (McAllister, 2004, p. 1168 emphasis added).

While McAlister is certainly right to say that in certain cases no conceivable actual experiment could display the phenomenon of free fall in accident-free form, this way of putting things somewhat confuses the issue. As I argue below, actual experimentation still played a crucial role for Galileo. Of course the phenomenon—in this case free fall in a vacuum—could not be realized in practice, as Galileo well knew, but the question remained—*how can we know how falling bodies of different specific gravities behave in a vacuum?* Koertge has argued, that in attempting to answer this question Galileo resorted to a number of different strategies at various stages. One early approach, which Galileo soon abandoned, according to Koertge's account, was to imagine the world with all accidents stripped away. A second way was to attempt to remove the accidents by technological means, but this proved to be impossible. In the *Discorsi*, Galileo finally hit upon the view that we must rely on knowledge gained from experience and extrapolate to the limiting case. As he makes explicit: "We must find and demonstrate conclusions abstracted from those impediments, in order to make use of them in practice under those limitations *that experience will teach us* (Galilei, 1974 [1638], pp. 225 emphasis added).

But what exactly does experience teach us? In order to answer his question, we need to look more closely at the situation that confronted Galileo. In the previous section, we saw that Galileo felt he had "clearly demonstrated that it is not true that unequally heavy bodies, moved in the same medium, have speeds proportional to their weights, but rather have equal [speeds]" provided we assume they are "of the same material (or rather of the same specific gravity)" (Galilei, 1974 [1638], p. 71–2). Here it is important to stress, as Palmieri reminds us, that Galileo "always considered it to be conclusive only under the very restrictive condition of bodies with the *same specific gravity*" (Palmieri, 2005, p. 224). This restrictive condition, which is explicit in the *Two New Sciences*, is often ignored in contemporary philosophical discussions.[8] In his early manuscripts, Galileo entertained the view that bodies of *different materials* might fall with speeds *proportional to their specific gravities* in a vacuum. Nevertheless, in the years that followed, Galileo had expressed doubts about the validity of this claim. By the 1630s the task he had set himself was to show that "if one were to remove entirely the resistance of the medium, all materials would descend with equal speed" (Galilei, 1974 [1638], p. 71). Yet this turned out to be an extremely complex and difficult task, which occupied Galileo for many years.

Galileo knew very well that bodies of different material (or specific gravities) fall at different rates in different fluid media. When two bodies of the same volume, but composed of different materials, such as gold and cork, are dropped in a given medium, like water, they will fall at different rates from one another. The same two bodies dropped in a less resistant medium, such as air, will also fall at different rates, but in this case, the *difference* in their respective rates of fall will be less than in water. The question for Galileo was whether this difference in rates of fall between the two balls would vanish altogether in the limiting case of a vacuum. The conceptual difficulties in answering this question become apparent when we consider that Galileo had by the 1630s abandoned his earlier hydrostatic model, according to which the speed of a falling body is proportional to the difference between its specific gravity and the medium's specific gravity. He now contended that there were four different forms of resistance exerted by a fluid medium on a falling body: (i) resistance due to buoyancy, which has the effect of making the body lighter; (ii) resistance due to the viscosity of the medium; (iii) the resistance due to the body's velocity—i.e. the faster the body moves, the greater the resistance; and (iv) the

[8] David Atkinson has criticised Galileo's thought experiment on the grounds that it does not take into account the hydrodynamic case of falling bodies in fluids of different viscosities. "Under the restriction of laminar flow, and for bodies of identical size and shape, … the viscous forces are proportional to the velocities, and so the terminal rates of fall are proportional, the times of fall inversely proportional, to the weights" (Atkinson, 2003, p. 210). As Atkinson explains, "it is true that two bodies, with different accelerations, if bound together, will thenceforth have an acceleration lying as an intermediate value", however, "if we interpret natural speeds as terminal velocities in a fluid with laminar flow, the situation is more complicated" (Atkinson, 2003, p. 211). While Galileo certainly had no concept of laminar flow, he did explicitly consider the effects of viscosity, adhesion and buoyancy of different fluid media.

resistance due to friction caused by adhesion between the body's surface and the fluid (Palmieri, 2005, pp. 232–5).

As Palmieri has argued, in an important surviving document in the *Postils to Rocco*, written in 1634, Galileo provided a semi-autobiographical account of how he approached this problem, which he there described as '*spuntar lo scolglio più duro*' [overcoming the hardest obstacle]. Here Galileo refers to a number of quantitative results that he had obtained for the time taken for certain material substances to fall over a certain distances through fluid media. Among the different substances Galileo discusses are a sphere made of beeswax mixed with lead, a cork sphere, a marble sphere, a sphere of pure gold, and spherical alloy of gold and silver. While Galileo does not explicitly refer to all these results in the *Two New Sciences*, published four years later, he does provide an account of the experimental conditions under which the different effects of resistance (in all the forms listed above) can be rendered negligible. Most notably, in this regard, he presents an ingenious series of experiments using a pendulum for observing the minute intervals of time that elapse between the arrival of heavy and light bodies when dropped from a small height in fluid media (van Dyck, 2005, pp. 870–1). The details of this experiment need not concern us here, but they form an integral part of an argumentative strategy employed by Galileo in answering the question he had set himself. Here it is worth quoting him at length:

> We are tyring to investigate *what would happen* to moveables very diverse in weight, *in a medium quite devoid of resistance*, so that the whole difference of speed existing between these movables would have to be referred to inequality of weight alone. Hence just one space entirely void of air—and of every other body, however thin and yielding—would be suitable for showing us sensibly that which we seek. Since we lack such a space, let us [instead] observe what happens in the thinnest and least resistant media, comparing with what happens in others less then and more resistant. If we find in fact that moveables of different weight differ less and less in speed as they are situated in more and more yielding media, and that, finally, despite extreme difference of weight, their diversity of speed in the most tenuous medium of all (though not the void) is found to be very small and almost unobservable, then it appears to me that *we may believe, by a highly probably guess*, that in the void all speeds would be entirely equal. (Galileo, 1974 [1638], p. 76 emphasis added)

There are two striking things to note about this passage. First, the question of whether bodies of different weights fall with the same rate in a vacuum, somewhat paradoxically, is to be decided empirically. Of course, it was impossible to ascertain this *directly* from experience. But it was possible to *extrapolate* from actual experimental observations to learn *what would happen in the idealized case*. While it is certainly true, as McAllister says, that "no feasible concrete experiment could have corroborated Galileo's claim" that all bodies fall at the same speed independent of their weight in a vacuum, it is not quite correct to say that he "sought knowledge about the world in thought experiment rather than in concrete experiment" (McAllister, 2004, p. 1168). Far from withdrawing from "the sphere of sense data", Galileo here made use of it. Secondly, Galileo does not describe his conclusion as something we can know on the basis of ordinary experience, nor as the result of demonstrative argument, rather as "a highly probably guess" based on careful observation and experiment. Galileo does not pretend to know in advance what would happen. Here we have what Koertge calls "the method of quantitative extrapolation from complicated, real-life, experimental situations to the ideal, theoretical, limiting case" (Koertge, 1977, p. 408).

Of course, one may ask whether Galileo really did carry out the decisive experiments he mentions in his account. This has been a perennial question in Galileo scholarship (Koyré, 1978; Drake, 1978; Naylor, 1979, 1989; Segré, 1980; Levere & Shea, 1990; Drake, 1990). Ernan McMullin suggests there is some doubt about "whether Galileo ever carried through the series of experiments with media with gradually decreasing densities and with bodies of different weight that he describes here" (McMullin, 1985, p. 267). Yet recent scholarship suggests that Galileo most likely did engage in a program of experimental investigation involving bodies of different materials in different fluid media (Damerow, Freudenthal, McLaughlin, & Renn, 2004; van Dyck, 2005; Palmieri, 2005; Renn, Damerow, & Rieger, 2000). As Palmieri has explained, "what might seem today as an instance of a very special form of cognition, which transcends empiricism, and might allow us a glimpse into the Platonic realm of laws, was born in the murky waters of analogical thinking, *ex post facto* cognitive autobiography, and in all likelihood real experimentation" (Palmieri, 2005, p. 238). Even if there remains some lingering doubt about whether Galileo actually performed these experiments, it is clear that the epistemic strategy presented in the *Two New Sciences* involves utilising the results of a series of carefully coordinated experiments, in attempting to settle the question of what happens in the ideal case.

The imaginary conditions of the thought experiment (e.g. a medium devoid of resistance) represent the limiting case of experimental conditions. But, it is one thing to *imagine the conditions* under which the phenomenon occurs. It is quite another to *know what would happen* under such conditions. In this case above, Galileo suggests that by observing what happens when bodies of different materials and weights are dropped in media of different resistances, one can extrapolate to the limiting case of a vacuum. This suggests one important way in which Galileo's epistemology of imaginary scenarios, at least in this particular form in his later work, differed from those of his medieval predecessors. Fourteenth century medieval thinkers like Albert of Saxony and Buridan did posit idealized scenarios, such as motion in a vacuum, but unlike Galileo, the conclusions they reached about what would happen in such scenarios were not justified by carefully extrapolating from a series of concrete experimental situations to the ideal limiting case.

6. Conclusion

It will be noted that I have only provided a small selection of thought experiments from Galileo's later writings. This is not intended to be exhaustive. However, even with this limited sample, we may now return to the question of whether, and to what extent, Galileo's use of thought experiments constituted a novel or distinctive way of doing science. Here there appears to be no straightforward answer. Once we realise that Galileo's thought experiments sometimes drew on the power of memory and everyday experience, while at other times, they took the form of demonstrative arguments, and on still other occasions, they drew on a carefully planned series of controlled experiments, it becomes evident that no simple account of the epistemological relationship between thought experiment, experience and experiment can adequately capture the variety of uses to which Galileo put imaginary scenarios in his writings. Here we must avoid the tendency to succumb to over-generalization. The epistemic variety we encounter here is perhaps to be expected, given that Galileo was writing at a time when the configurations of European natural knowledge were shifting, and the proper methods and aims of natural knowledge, as well as the scope of application of logic and rhetoric, were the subject of much debate and disagreement. The particular forms of reasoning that appear in Galileo's use of thought experiments might perhaps provide a unique snapshot into the epistemological turmoil of the 17th century.

This is not to say that thought experiments in other eras would also not display a variety of epistemic strategies. Indeed I expect they would. My claim is that the particular epistemic strategies that Galileo employed in his thought experiments reflect the intellectual context—and the shifting patterns of rhetorical argument and epistemology—characteristic of the early seventeenth century. A proper answer to the question of what, if anything, was distinctive about Galileo's use of thought experiments, would require a comparative historical analysis of the various ways in which imaginary scenarios were employed by other authors in the fifteenth and sixteenth centuries. This is a task clearly beyond the scope of this paper. Yet it is interesting to note that one of the obstacles to a better understanding of Galileo's thought experiments has been the tendency to impose a false dichotomy between experiments and thought experiments on his work. While this dichotomy certainly seems appropriate for the second class of thought experiments I considered, which aimed at the construction of demonstrative arguments, and which explicitly go beyond a reliance on concrete experiments to establish their conclusions, it does not really capture the way in which experiments were deployed in other instances, for example, in considering what would happen to bodies of the same material falling in a vacuum. Extrapolation from experiment, rather than emancipation from it, was characteristic of this type of thought experiment.

The historiographical and philosophical approach adopted in this paper centres on the notion of epistemic strategies used in the contemplation of imaginary scenarios. Here I suggest that a shift of focus away from *aim* and *function* of thought experiments in science, which has been the subject of much philosophical analysis, to the question of *how thought experimenters know what would happen in an imaginary scenario*, brings into sharp focus a number of important points, which may guide further historical investigation into thought experiments. First, it highlights the need to abandon thought experiment as a 'unitary epistemic category'. In spite of the lip service frequently paid to this point, much of the literature focusing on thought experiments continues to draw rather general conclusions about what they are and the forms of reasoning they employ. Secondly, this shift of focus brings to light the point that thought experiments are not in themselves sources of knowledge. Rather, it should be stressed that in considering an imaginary scenario, the reader is called upon to draw upon other existing sources of knowledge. These may include everyday experience, empirical knowledge gained though careful observation and experiment, or even high-level theory. Thirdly, thought experiments may employ certain distinctive rhetorical structures and forms of reasoning in attempting to persuade the reader of the conclusions reached by the author.[9] This brings us finally to a fourth point—that the very categories of explanation or rhetorical strategies that are invoked in thought experiments may reflect the wider intellectual context, or a particular epistemic style. Recognition of this last point might well provide a means for 'historicizing' and 'contextualizing' thought experiments. In this way, a focus on epistemic strategies may prove useful in studying the distinctive forms of reasoning we find in the thought experiments of different figures or different eras by situating them within specific disciplinary contexts and intellectual traditions.

[9] I thank the editors from this suggestion.

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