

The Paradox of Conceptual Novelty and Galileo's Use of Experiments

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Starting with a discussion of what I call 'Koyré's paradox of conceptual novelty', I introduce the ideas of Damerow et al. on the establishment of classical mechanics in Galileo's work. I then argue that although their view on the nature of Galileo's conceptual innovation is convincing, it misses an essential element: Galileo's use of the experiments described in the first day of the *Two New Sciences*. I describe these experiments and analyze their function. Central to my analysis is the idea that Galileo's pendulum experiments serve to secure the reference of his theoretical models in actually occurring cases of free fall. In this way, Galileo's experiments constitute an essential part of the meaning of the new concepts of classical mechanics.

1. Introduction. The emergence and establishment of classical mechanics has always served as a prime example for debates on the nature of science and its conceptual development. Accordingly, its study has often been a place for a fruitful interaction between history and philosophy of science. Galileo has since long been an emblem for modern experimental science (for a recent example see Boumans 2003). At the same time, Galileo's own use of experiments has been a hotly debated topic during the past century. This paper is intended to shed some light on the role that one set of experiments played within Galileo's science. Although of historical interest, it must primarily be seen as contributing to the discussions on the nature and function of different types of scientific experiments, discussions of which have been gaining momentum in the philosophy of science over the past two decades.

In Section 3, I will discuss Galileo's use of the experiments with a pendulum that he describes in the first day of his *Dialogues Concerning Two New Sciences* (Galileo [1638] 1954). I ascribe to these experiments a

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much more central role in Galileo's science than is usually admitted. In Section 4, I will analyze the light this sheds on the paradox of conceptual novelty, which will be introduced in Section 2.

2. The Paradox of Conceptual Novelty. Alexandre Koyré is famous (in some quarters, infamous) for denying that experiments played any fundamental role in Galileo's establishment of his science (see especially Koyré [1939] 1966, 1968). He gives two arguments for this claim. They are connected, but the falsity of the first doesn't imply that we can neglect the second (although there has been a tendency to do so). After extensively quoting Galileo's description of his inclined plane experiments in the *Two New Sciences*, Koyré, in a typical example showing the essentially rhetorical nature of the first argument, remarks: "It is obvious that the Galilean experiments are completely worthless: the very perfection of their results is a rigorous proof of their incorrection" (Koyré 1968, 94). Of course, Koyré is right in remarking that Galileo must have exaggerated the results of his experiments, but this need not imply that Galileo did not perform them. Indeed, extensive research on his manuscripts has revealed that Galileo did perform experiments with inclined planes, and moreover, that at least some of his results were in essential agreement with his theory (for a recent assessment of these experiments, see Hahn 2002). What should be remembered, however, is that Koyré had a philosophical motivation for making provocative claims like the one quoted. This provides a second argument for denying experiments a fundamental role. At several places Koyré admits that Galileo might well have had an experimental program (although he didn't execute it properly), but he stresses that these experiments can only consist in the testing of well-formulated theoretical claims (Koyré [1939] 1966, 143, 155). For an experimental mathematical science such as classical mechanics to be possible, *a theoretical language must first be established*. Experimental results cannot be at the foundation of a new mathematical science; they can only come at the end, in the form of nature's answers to theory's questions (Koyré [1939] 1966, 13, 156; Koyré 1968, 75–76). Before experiments establishing the law of fall were possible, the very idea of motion already had to be re-conceptualized.

Koyré was not the first to make this philosophical point. A famous forerunner was Pierre Duhem ([1906] 1914). Both Koyré and Duhem oppose a naïve "abstractive empiricism," which would see the establishment of mathematical science grounded in inductive generalizations from empirically observed regularities. As Duhem incessantly stresses, this goes counter to the symbolic character of any truly mathematical science. Before an experimental fact can become epistemologically relevant for a mathematical physical theory, it must first be translated into a symbolic

language. This implies that the conceptual structure of the theory must already be established before an empirical fact can have any epistemic bearing on this theory. Koyré shares this insight, but couples it to a view which sees the historical development of physics as characterized by a discontinuous break during the scientific revolution (a term which he understandably championed). In Galileo's work we see the replacement of one conceptual whole for another one. (The link with Thomas Kuhn's ideas is obvious, and Kuhn stressed his indebtedness to Koyré (Kuhn [1962] 1996, 3).)

We seem to be presented with a paradox: where do Galileo's new concepts come from, if they cannot be abstracted from experimentally established regularities? Whence conceptual novelty? Koyré had an answer: Galileo's metaphysical inclinations, his "Archimedean Platonism," guided and structured his conceptual revolution—metaphysics is what makes measurement possible. Undoubtedly, this solution sounds rather naive, and Koyré's answer doesn't stand close scrutiny, but the problem that he raised is genuine.

In their brilliant study, Renn et al. (2000) tackle the problem of Galileo's conceptual novelty and propose an ingenious solution, based on a careful study of all the relevant material. By focussing on Galileo's proof techniques, they show in compelling detail how he was struggling to derive theorems which are valid in classical mechanics by means of a conceptual apparatus which was still "preclassical." Nevertheless, the generation of scientists immediately following Galileo could take these theorems as their starting point, and let them dictate the appropriate conceptual framework, which then became "classical."

Thus, while for the first discoverer, the law of free fall is achieved by applying and modifying an independently grounded, pre-existing conceptual system, for his disciples it is the law of fall that canonically defines key concepts in a new conceptual system. The very same reading of these theorems that establishes classical mechanics also obliterates the traces of its real historical genesis because the original problems and the concepts involved are now understood within a very different theoretical and semantic framework. But since the successors themselves derive the inherited theorems on the basis of the new concepts, they impute these concepts to the discoverers. (Damerow et al. 2004, 5)

To properly solve the riddle of Galileo's conceptual novelty, it is necessary to push back the borderline. Galileo's science at the same time was continuous with a preclassical conceptual system, and did constitute a break with it—for those who came after him. I believe that this will prove to be a lasting insight. Nevertheless, I also believe that Damerow et al.

overlook something that is crucial to fully characterize how this break was made possible by Galileo's work. But let me first expand a little bit on the mechanism for conceptual transformation that they propose.

The results achieved by Galileo implicitly define a new conceptual structure. These results were reached by applying given conceptual means to peculiar problems. The nature of these problems, although defined in terms of the given conceptual apparatus, forced Galileo to stretch the limits of application of these conceptual means, showing the need to transcend this conceptual apparatus. Through his exploration of these limits, Galileo's work already implicitly started the necessary conceptual restructuring. Thus, the nature and origin of these problems becomes an important question.

Damerow et al. locate two possible sources that can force someone like Galileo to explore the limits of his conceptual apparatus: the introduction of new objects of investigation, and the combination of conceptual means that stood unconnected before. It is on the first of these that I want to focus. The most important new object with which Galileo was confronted was naturally accelerated motion, and more specifically the knowledge that the space traversed by such a motion was as the square of time spent in this motion.¹ His attempts at trying to incorporate this knowledge into a theoretical framework forced him to stretch his conceptual apparatus, which was not suited to handle accelerated motion in an unproblematic way. Hence, at the basis of Galileo's implicit conceptual restructuring there lies empirically given information. As I will show in Section 4, by conceiving of this information as "given," an essential element of the conceptual transformation brought about by Galileo remains hidden.² But first I will have to go back to the first day of Galileo's *Two New Sciences*.

3. Galileo's Use of Experiments. The task Galileo set himself in constructing a mathematical science of motion was to bring the diverse elements involved in the phenomena of local motion into a well-determined relation, capable of being manipulated with his geometry of proportional magnitudes. If a stable model for the free fall of bodies could be constructed, a host of properties surrounding the motion of bodies could be

1. Renn et al. (2000) provide definitive proof that as early as 1592 Galileo knew that projectile motion has an approximately parabolic shape, and that he thereafter could have derived a quadratic dependency between space and time.

2. It is true that Renn et al. (2000)—Jürgen Renn is also credited with writing the chapter on Galileo in Damerow et al. (2004)—stress that such information in itself is not just "given." It must be perceived as relevant, and this involves important contextual factors. This is indeed a very important qualification, but as will become clear, I want to point at still another qualification of this "given" character.

analysed and investigated, thanks to the powerful and secure ways of mathematical reasoning. As is well known, Galileo succeeded—within the limits set by his conceptual apparatus—by considering the fall of bodies in a void, a limit situation in which all bodies undergo the same uniform acceleration.

3.1. Extrapolating to the Vacuum. In the first day of his *Two New Sciences*³ Galileo leads the reader through a series of experiences, thought-experiments, and what we would recognize as genuine “experiments,” all adducing crucial insights on the phenomenon of free fall. He starts by demonstrating the physical falsity of the Aristotelian teaching on the subject.

First, experience and a clever thought experiment show that the velocity of falling bodies cannot be directly proportional with their weight. Furthermore, the velocity of falling bodies cannot be inversely proportional to the density of the medium through which the bodies fall. Such a relation implies that negative speeds (or speeds equal to zero) cannot be obtained in any medium, whereas experience clearly shows that some bodies that fall through air, move upwards in water (or are in equilibrium).

Thus far, falsifying Aristotle’s statements, Galileo has considered two kinds of situation: different bodies falling through the same medium, or one body falling through different media. At this point he announces: “I then began to combine these two facts and to consider what would happen if bodies of different weight were placed in media of different resistances. . .” and he immediately gives the result “. . .and I found that the differences in speed were greater in those media which were more resistant, that is, less yielding” (113). If two bodies that fall through air at almost exactly the same speeds, are observed when falling through water, much greater differences in speed can be remarked, an observation from which quickly follows the extrapolation: “Having observed this I came to the conclusion that in a medium totally devoid of resistance all bodies would fall with the same speed” (116).

At this point Galileo has falsified not only Aristotle’s theory, but also the one he had defended himself in his earlier *De Motu* (probably written around 1590–92) (Galileo 1960). In that work, Galileo had modelled the phenomenon of free fall on hydrostatic phenomena, claiming that the speed of a falling body is proportional to the difference between its specific gravity and the medium’s specific gravity (anachronistically, we can say that he replaced the “Aristotelian” ‘ $v \sim W/R$ ’ with something of the form

3. I will quote from the translation by Crew and de Salvio (Dover, 1954), and parenthetically give page references to the (standard) National Edition (ed. Favaro), as also indicated in the Dover edition.

‘ $v \sim w - r$ ’). (It was a well-known fact from the science of hydrostatics that the effect of a medium is to make a body weigh less.) This model would imply that in a void, the speeds of different bodies would stand in the same ratio as their specific gravities, and that the differences in speed should become less perceptible in more resisting media. Nevertheless, as was already pointed out by Dijksterhuis (1924), in essential agreement with the central thesis of Damerow et al., Galileo still seems to be working with the same set of concepts in his later theory. The major difference is that his theorizing is now more constrained by empirical information. This comes out most clearly when we consider how Galileo treats the fact that in resisting media different bodies do have different speeds.

3.2. *Calculating the Differences.* Galileo doesn’t stop with the claim that in vacuum all bodies would fall with the same speed. Still taking into account the hydrostatic model, but this time constrained by his empirical findings, he now argues that what is really relevant to understand this is the disproportionate way in which bodies of different specific gravity are alleviated in different media. It is true, he remarks, that in a medium there is always a resistance to be overcome for a body moving in free fall, and we know that “the weight of the medium detracts from the weight of the moving body, which weight is the means employed by the falling body to open a path for itself and to push aside the parts of the medium. . .” (119).

Galileo makes this clear by a number of examples. Suppose that lead is 10,000 times as heavy as air while ebony is only 1000 times as heavy, and let water be 800 times as heavy as air. The effect on the alleviation of lead, in going to a denser medium such as water, will be negligible compared with the effect of the denser medium on the specific gravity of ebony. Although they have the same “unhindered speed” (121), the speeds of ebony and lead in dense media will differ considerably, due to the greater difficulty suffered by ebony in overcoming the obstacle posed by the medium. This “buoyancy effect” of the medium would be calculable in principle, provided all the absolute specific gravities were known, i.e. the specific gravity measured with respect to vacuum, and not with respect to air. The formula that would translate Galileo’s explanation in an algebraic form would be: $v = v_0[w(\text{body}) - w(\text{medium})]/w(\text{body})$ (with ‘ $w()$ ’ the specific gravities, ‘ v_0 ’ the unhindered speed, and ‘ v ’ the speed in a medium) (Dijksterhuis 1924, 229; Clavelin 1968, 340, n. 31).

3.3. *Experimentally Isolating the Differences.* This is not all. A medium not only alleviates, it also has a frictional effect, which is dependent on the speed of the falling body. “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 constantly accelerated" (119). At this stage, Galileo no longer has a theoretical model which would allow him to calculate the difference a medium makes on the fall of different kinds of bodies. However, he will show how *to isolate experimentally what differentiates the behavior of these bodies*.

Galileo is in particular interested in the differences that might arise between dense and light bodies when they fall over long distances, as he suggested himself that this might pose a problem for his hypothesis of equal unhindered speeds: in these circumstances, and even in a rare medium such as air, dense bodies will outstrip the light ones with considerable distances. Since such an observation poses practical problems, Galileo suggests an ingenious experimental setup, mimicking this situation. "It occurred to me therefore to repeat many times the fall through a small height in such a way that I might accumulate all those small intervals of time that elapse between the arrival of the heavy and light bodies respectively at their common terminus, so that this sum makes an interval of time which is not only observable, but easily observable" (128). The experimental device standing in for fall over great distances is a pendulum, and the assumed isochronity of the pendulum swings will be the clue to Galileo's analysis.

When two balls, one of lead and one of cork, are made to swing on identical pendulums, two facts may be observed, Galileo claims. The swings of the different balls remain isochronous with each other, while the amplitude of the cork ball will diminish much more swiftly. That the swings remain isochronous implies that *when* the two balls traverse equal arcs, they do so in equal times: the greater retardation of the lighter body cannot be due to an inferior natural speed. Hence, there can be no direct correlation between the different specific gravities of the bodies and the different speeds if they fall over long distances. All differences that do arise must be due to the effect of the medium on the bodies, and this effect can thus be shown present in the (differing rate of) diminution of the amplitudes. Since the buoyancy effect is only dependent on the ratio between the specific gravities of the falling body and the medium, which is constant and hence cannot be responsible for a diminution of speed (as witnessed by the shrinking amplitudes), the friction effect must be the cause of the change in speeds. As a final conclusion we can infer that the friction effect will be greater for bodies with a smaller specific gravity, hence explaining why dense bodies outstrip light ones.

3.4. Function of the Pendulum Experiments: Securing Reference. Let us take stock of what Galileo has achieved with these discussions presented in the first day. He has shown that a stable model for free fall can be

constructed by considering the situation of fall in a vacuum—since in this case all bodies will exhibit the same behavior, independent of their specific weight. Remark that he has not yet established the exact relations constituting such a model: this will only be done in the third day where the quadratic dependency will finally find its place. *That the model thus constructed will still be relevant for actually occurring instances of free fall, is secured by his particular experimental procedure, guaranteeing that the case of fall in a void is not merely the simplest case, but the most general.* By isolating all that actually differentiates different kinds of bodies with respect to the phenomenon of free fall, it becomes possible for Galileo to attribute the presence of the “pure phenomenon” to actually occurring instances of free fall, even if these might show considerable deviations from the theoretical models. To put it in a language familiar from contemporary philosophy of science (cf., e.g., Pickering 1981 and Galison 1987), Galileo has established what a closed system with respect to the phenomenon of free fall consists in. He has shown how to separate the pure phenomenon from possible disturbances, how to retract a meaningful signal from the noisy actual behavior. To put it in a language relevant for the discussions on conceptual novelty: *Galileo has experimentally secured the reference of his theoretical models.*

Naylor (1989) stresses that there is an important shift within Galileo’s work from what he calls a pre-empirical episteme towards a much more modern attitude in his later work such as the *Two New Sciences*. Nonetheless, he doesn’t ascribe any central role to the pendulum experiments in this respect. This is also testified by an earlier article where he claims that these experiments merely served a didactic purpose (Naylor 1976). Compare also Hill (1988), who sees these experiments as “a means of shoring up soft spots in his geometrical exposition” (Hill 1988, 666). It is clear that, contrary to these authors, I perceive an epistemologically deep role for these experiments. They assure Galileo that in principle, he can transpose to other cases results that are strictly valid only for a vacuum (although he is not able to calculate all the effects of the medium in advance, in the fourth day he does describe experimental means to estimate the effects). This is what is meant by saying that these experiments show that fall in a vacuum is not merely the simplest case, but the most general.

Admittedly, we can no longer accept Galileo’s description of the disturbances: His understanding of the effect of a medium is conceptually confused (cf. Westfall 1971, 30–36), and the frictional effect is not linear with speed (cf., e.g., Naylor 1976). But this doesn’t impinge upon the *function* that his experiments with the pendulum have within Galileo’s science.

4. Galileo's Experiments and Conceptual Novelty. The main flaw of Koyré's treatment of the problem of conceptual novelty is that he isn't sufficiently aware of the way new concepts can be implicitly constructed by putting older concepts to new uses. This neglect is what makes conceptual novelty appear paradoxical. However, as shown by Damerow et al., this construction is far from straightforward. I will now argue that they also overlook an essential element entering into this construction.

As was explained in Section 2, central to the argument of Damerow et al. is the idea that Galileo's exploration of the limits of preclassical mechanics implicitly defined the concepts of classical mechanics. This exploration was triggered and constrained by the attempt to apply the preclassical concepts to the problem of accelerated motion. True, but I want to stress that Galileo's conceptual restructuring was not only constrained but also positively controlled by experimental means. He was not only trying to incorporate empirical information into his conceptual framework, but also experimentally reworking the problem situation. Galileo was not only stretching the limits of application of his preclassical concepts, but also experimentally investigating the proper domain of application for a true science of falling bodies. The stabilization of concepts is not independent of the stabilization of the empirical situation. The implicit definition of the classical concepts is co-constituted by the application of the preclassical concepts to carefully selected, and not as such given, situations. By establishing that the case of fall in a void was the most general, and hence could be called the *natural* behavior of bodies, Galileo did pave the way for what would become the central domain of application of classical mechanics. The transition from an Aristotelian dynamical framework to the Newtonian is unthinkable without this intervention.

Rose-Mary Sargent has aptly remarked that experiment constitutes a third methodological category that mixes elements from classical empiricism and rationalism (Sargent 1995, 231, n. 50). This also holds true with respect to the problem of conceptual meaning. The meaning of modern scientific concepts is fully determined neither by the conceptual structure of which they are a part, nor by the empirical objects, or properties, or whatever, to which they are supposed to refer. It is only the way that these aspects are put together by experimental means that gives these concepts their full meaning. At the same time, the character of the situations thus described takes on a new dimension.

As a result of Galileo's experimental analysis, it becomes possible for him to attribute the presence of the pure phenomenon to actually occurring instances of free fall, transforming the character of the latter through this attribution. From now on, it will become possible to speak meaningfully about the velocity and the acceleration of the falling objects, and

especially about the (mathematical) relations obtaining between them, as defined and analyzed at the theoretical level of the new science. At the same time, the meaning of the abstract concepts of velocity and acceleration will be co-constituted through this attribution. The experiments with the pendulum are essential to all this, because they secure the reference of the pure phenomenon in non-pure situations. In contradistinction to Koyré's view, the abstractly floating concepts are tied to empirical reality from the beginning.

What I called the paradox of conceptual novelty is related to the well known riddle of the applicability of mathematics to nature. That new concepts cannot be abstracted from empirical knowledge—this would not be paradoxical if these concepts were not supposed to constitute a physical science, i.e., be applicable to nature. Galileo famously claimed that the book of nature is written in a mathematical language, but the preceding discussion reveals how the reading of that book can only take place via the mediation of experimentally constructed situations. Experimental activity is what makes possible a mathematical science of nature, by securing the reference of theoretically defined concepts.

5. Concluding Remarks. It is clear that the perspective I have taken here is informed by the so-called “new experimentalism” that found a very influential and early expression in Ian Hacking's *Representing and Intervening* (Hacking 1983). Hacking was very effective in drawing attention to the multiple functions that experiments can have, other than confirming or falsifying theoretical claims. Experiments not only “give” empirical content to theories, but also have a structure that shapes this content. My critique of Damerow et al. has exactly been that they focus too exclusively on the way Galileo represented problems. By intervening experimentally he also reconstituted these problems, transforming their nature in a way that was essential for the establishment of the new conceptual structure of classical mechanics.

Both Galileo's experiments leading up to the extrapolation to the situation of fall in a void (Section 3.1), and his experiments with the pendulum to exhibit the presence of the pure case of free fall in actually occurring instances (Section 3.3), show many of the characteristics of what Friedrich Steinle has called “exploratory experiments”: “Exploratory experimentation . . . is driven by the elementary desire to obtain empirical regularities and to find out proper concepts and classifications by means of which those regularities can be formulated” (Steinle 1997, S70). He also stresses that, in this respect, “of particular importance is the idea of elaborating ‘pure’ or ‘simple’ cases” (S73). I am in complete agreement with Steinle's insistence on the fact that these kinds of experiments can be epistemologically very relevant and should not be relegated to some

kind of mystical “context of discovery.” One important difference between the cases he discusses, and the case of Galileo discussed here, is that Galileo was not merely exploring experimentally, but exploring the limits of his conceptual apparatus at the same time (as described by Damerow et al.). A truly satisfactory picture can be gained only by focussing both on how he was representing and on how he was intervening.

Let me fittingly end by linking Galileo’s work with his pendulum, trying to retract a meaningful signal from the noisy actual behavior of falling bodies, to the work of that other Florentine giant.

Michelangelo was once asked how he had carved his marble masterpiece. The sculptor apocryphally responded that nothing could be simpler; all one needed was to remove everything that was not *David*. In this respect the laboratory is not so different from the studio. As the artistic tale suggests, the task of removing the background is not ancillary to identifying the foreground—the *two tasks are one and the same*. (Galison 1987, 256)

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