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ARTICLE

Can the History of Science Contribute to Modelling in Physics Teaching?

The Case of Galilean Studies and Mario Bunge's Epistemology

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Abstract A characterization of the modelling process in science is proposed for science education, based on Mario Bunge's ideas about the construction of models in science. Galileo's *Dialogues* are analysed as a potentially fruitful starting point to implement strategies aimed at modelling in the classroom in the light of that proposal. It is argued that a modelling process for science education can be conceived as the evolution from phenomenological approaches towards more representational ones, emphasizing the role of abstraction and idealization in model construction. The shift of reference of theories—from sensible objects to conceptual objects—and the black-box models construction process, which are both explicitly presented features in Galileo's *Dialogues*, are indicated as highly relevant aspects for modelling in science education.

1 Introduction

Ideas such as light rays, atoms, species, centres of mass, among many other abstract scientific concepts, are constantly present in science classrooms. Nevertheless, very little attention is directed towards the relationship between these abstract concepts and the realities to which they are supposed to relate. As a consequence, scientific models as presented by teachers can be perceived by students as ontologically real entities (Taber 2012). That being said, it should come as no surprise that students find it difficult to reconcile scientific knowledge learned in school with their experiential reality. Real objects around them are not frictionless nor moving in linear uniform motion. As Cartwright (1983) argues in her "*How the laws of physics lie*", these laws do not tell us what real

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objects do. But even when teaching practice includes discussions about the restricted domains of validity of theories, it is rarely emphasized how laws and theories apply to an idealized world. The approximate character of scientific knowledge could be shown by analysing situations in which the laws being studied do not apply. However, this kind of counterexample is rarely presented in classroom. In addition, if teaching practices are not concerned with the relation between theory and reality, it might seem reasonable for students to conclude that there is no relation whatsoever. Modelling theory can be introduced in science education in this context.

In the philosophy of science, the theme of models and modelling emerged more strongly from the 1960s, impelled by the works of Rom Harré, Mary Hesse, Mario Bunge, Ronald Giere, among others. A feature that seems consensual among these studies is the idea that models are not secondary or auxiliary elements, but instead they occupy a central position in scientific knowledge construction. The main question addressed in these studies can be expressed with the following question: How does scientific knowledge relate to reality? Obviously there is no single, uncontested answer, but we believe that this is an important issue to be discussed in science education contexts and that modelling practices can help both students and teachers think more critically about the objects and theories of science.

In science education research, this theme can be traced at least from the 1970s (Ormerod 1978; Sutton 1978), but received impetus especially during the 1990s and 2000s, with comprehensive studies being developed by Gilbert and his collaborators (Gilbert and Boulter 1998; Gilbert et al. 1998, 2000; Justi and Gilbert 2000), David Hestenes (1992, 1997, 2010), among many other considerable contributors. Despite their broad recognition in the science teaching literature, these models vary widely in how they are used and understood by teachers and researchers, their perceived functions in teaching and learning science, and their assumed ontological status. For instance, in some studies, building a model is considered as establishing analogies or metaphors with more familiar, well-known situations or objects (Galagovsky and Adúriz-Bravo 2001; Dupin and Johsua 1989; Harrison and Treagust 1996). Other works tend to emphasize mathematical features of model building, such as functions relating some of the problem's variables (Uhden et al. 2012; Redish 2005; Angell et al. 2008). The main purpose, however, seems to remain the same: an attempt to form a link between theory and phenomena, therefore making theories as comprehensible as possible for students. In this sense, the present study is aligned with Gilbert et al. (2000), for whom "…modelling and models must be seen in a broader context, that of the relationship between notions of 'reality', 'theory' and 'model'…" (Gilbert et al. 2000, p. 19).

In discussing how there could be a link between theory and reality, we are led to consider the role of abstraction and idealization in science. Recognizing the existence and the importance of these processes derives from understanding that the laws of nature are not in nature itself; they can only be directly applied to an idealized world. But at the same time, this idealized world is not merely a fantasy or a product of imagination alone; instead, it is created with a realistic intention, that is an attempt to conceptually represent the natural world.

Modelling in science teaching can thus be understood as an attempt to explain reality through a creative process where scientific knowledge is used as a mediating frame of reference. The most typical ways suggested to implement modelling in science teaching, as they appear in the science education literature, usually involve establishing analogies, metaphors, exploring mathematical skills, or developing some kind of experimental activity. Nevertheless, history and philosophy of science (HPS) has also been pointed out as a possible approach to discussing models in science education (Justi and Gilbert 2000;

Matthews 2007). In this study, we suggest further development in this direction and argue that the didactic use of the history of science—in particular, Galilean studies—can be a fruitful strategy to implement practices aimed at modelling in the classroom. In order to do so, first we seek to deepen our understanding of the modelling process based on Mario Bunge's epistemology. Next, we analyse Galileo's *Dialogues* as explicit modelling examples. The relevance and fruitfulness of examining Galileo's work in order to understand some important features of modern science, especially those related to idealization, are deeply discussed in Matthews (2000, 2005).

Although less present in model-based approaches and discussions in science education than other philosopher's, Mario Bunge's ideas were chosen to support this study because they provide a clear and fruitful explanation about the link between perceived reality and the scientific knowledge that attempts to represent this reality through his notion of a "model-object". His ideas also offer a systematic view on how both theoretical and empirical domains contribute to constructing models, which in turn can be understood as a mediating stance between them. Inasmuch as his ideas help in understanding the relationship between reality, theory, and model, we consider that they have a potential to allow for interesting insights into modelling strategies for science education. In addition, as noticed by Gilbert et al. (2000), these ideas can be intelligible to students provided that suitable examples are offered.

However, as idealizations and abstractions play a major role both in the modelling process and in Galileo's works, we begin by discussing these two concepts.

2 Idealizations

Ernan McMullin distinguished different forms of idealization employed by Galileo in his works, all of which became characteristic of modern science. Taking a conceptual–historical approach, this author described and exemplified (mainly from Galileo's *Dialogues,* but also from Newton, Bohr, and others) his categories for the notion of idealization in science. He considered *idealization*, in general, as a rather loose term, meaning "…a deliberate simplifying of something complicated […] with a view to achieving at least at a partial understanding of that thing" (McMullin 1985, p. 248). This complicated thing being simplified can be, in McMullin's account, either the object or situation itself or its conceptual representation. The first case is called *causal* idealization, meaning the act of eliminating or neutralizing influences that impede or complicate the action of the factors one is trying to study. This could be done *experimentally*, as suggested in Galileo's *Dialogues* (whether he actually carried out his experiments is an entirely different issue) and would allow isolating one single cause. Neglecting the effect of resistance, for example, would be a causal idealization assumed by Galileo in order to infer that all movables would fall with the same speed in the void. What made McMullin (1985) consider it "experimental" is the fact that Galileo appealed to experimental arguments to make this statement: he compared the behaviour of bodies falling in "thinnest and least resistant" media with other "less thin and more resistant" ones and reached the void as a limiting case.

But causal idealization can also be developed without invoking any actual experimental result, based just on appealing to everyday experience or intuition. This was called by McMullin (1985) *subjunctive* idealization, and it results in assertions about the world that are taken for granted, without resorting to any concrete experimentation. McMullin exemplifies this with the case of Galileo' argument for the problem of the stone dropped from the mast of a moving ship. Although Galileo could easily propose an experimental argument to demonstrate his point, he explicitly chose not to: "Without experiment, I am sure that the effect will happen as I tell you because it must happen that way" (Crew and de Salvio 1914, p. 145). Instead, Galileo resorts to the uniform horizontal motion, which "would be perpetual if the plane were of infinite extent", something that he could not obtain experimentally.

On the other hand, simplifications carried out on the conceptual representation of an object or event are called *construct* idealizations. In them, "…the models on which theoretical understanding is built are deliberately fashioned so as to leave aside part of the complexity of the concrete order" (McMullin 1985, p. 273). Therefore, while causal idealization means eliminating some of the aspects that influence the object, construct idealization refers to simplifying the aspects chosen to be taken into account in the model. The fact that Galileo develops abstractions and idealizations as legitimate thought processes in scientific activity is made very clear by the reading of his *Dialogues*. In fact, these two processes are so important to the emerging new science advocated by Galileo that McMullin (1985) grouped all his idealizations' categories under the broad term "galilean idealization".[1]

An important remark made by McMullin (1985) is about the *purpose* of idealizations in science. According to him, idealizing is not just a way to escape from the complexity of real physical situations, but it also allows the development of theoretical models that are intended to have explanatory power. This role of idealizations in modelling could be performed in two main ways. One of them is by establishing simplifications or omissions regarding properties that are *known* to be relevant to the kind of explanations being developed. This kind of idealization is called *formal* (McMullin 1985). It can be frequently (though not necessarily) mathematically expressed and is useful to obtain approximate results. Considering the Sun to be at rest—as Newton did when he derived Kepler's Laws in the *Principia*—would be an example of this type of idealization.

The other way idealizations take part in modelling is by allowing some features to be simply left unspecified, though they are left open for question in a different context or approach. This second aspect of idealization is called *material idealization*. When McMullin exemplified material idealizations, he mentioned the case of the kinetic theory of gases. This model postulates the existence of molecules as constituents of gases and does not specify any internal structure for these molecules. In McMullin's perspective, the question about what is inside a molecule is simply unasked and deemed irrelevant in the kinetic theory, although the possibility of an internal structure is not denied. Both formal and material idealizations are considered by him to be subcategories of construct idealizations.

Our main interest is not to propose a strict definition for each one of these processes, but instead we want to investigate the role of abstractions and idealizations to modelling in physics teaching. For this purpose, we maintain relatively flexible concepts for abstractions and idealization as operations performed by the epistemic subject that involve omitting features and variables and simplifying the nature of the objects being studied. Also, we emphasize the fact that this process results in an idea about a real object or event. In order to understand how such ideas can possibly be used to develop explanations about the world

[1] McMullin did not claim that Galileo invented all of them; instead, he tried to emphasize that all of them played a significant role in the development of the new science advocated by Galileo (McMullin 1985).

they represent, we need to turn to modelling as a process of producing scientific knowledge.

3 The Modelling Process from Mario Bunge's Perspective

Mario Augusto Bunge is a physicist and philosopher born in Argentina in 1919 and is currently the Frothingham Professor of Logic and Metaphysics at McGill University in Canada. A diverse and prolific scholar, Bunge is author or editor of around 70 books and 500 scientific or philosophical papers in a large number of teaching and research topics, including physics, philosophy, ontology, metaphysics and philosophy of science. Studying the interaction between science and philosophy has been a life-long commitment in Bunge's scholarly work (Matthews 2003), and his epistemological ideas about scientific models are an example of that. Bunge's *Treatise on Basic Philosophy*, considered his Magnum Opus, encompasses semantics, ontology, epistemology and ethics in eight volumes, divided in nine parts. Three volumes are devoted to epistemology: volume V: *Epistemology and Methodology I: Exploring the World* (1983a); volume VI: *Epistemology and Methodology II: Understanding the World* (1983b); and volume VII: *Epistemology and Methodology III: Philosophy of Science and Technology* (1985).

Bunge highlights the central role of models in scientific activity. To him, the essence of scientific knowledge is its partial and approximate character (Bunge 1973). Therefore, theories and models of physics refer immediately to conceptual objects and only mediately to real objects (Bunge 1974, p. 36). This mediate reference means theories and real objects are connected indirectly, having conceptual objects as intermediate agents. These conceptual objects are called *model-objects*, and they are a result of thought operations performed by the epistemic subject. This is why abstractions and idealizations are so important to scientific knowledge construction. It is not simply because it is impossible to capture all the complexity of any real system or object, but it is especially useful for providing a conceptual counterpart that eventually allows one to explain this complex reality.

Model-objects are schematic representations of real objects. However, the word "schematic" here does not mean pictorial or figurative. Model-objects have to be conceptual, since they are essentially *ideas* about their referents. This aspect is what allows them to be embedded into broader theoretical frameworks. Their schematic character alludes to the fact that they miss some of their referent's traits, since they are created through abstractions and idealizations (Bunge 1973). Taking the brain as a network of neurons, the Moon as a point mass, or solid matter as a crystal lattice can be cited as examples of using constructs to represent things, and that is what the model-object stands for. This concept shows that the non-identity relationship between the objects of reality and the knowledge produced about these objects is an important feature of Bunge's epistemology.

We believe that inadequate ways of establishing this relationship are common in school practices of physics and can lead students to the perception that physics does not relate to reality. Therefore, the possibilities of dealing with these issues pass through an understanding of abstraction and idealization processes that allow the construction of a model-object.

But model-objects alone have no explanatory power. To create an explanation would require the development of what Bunge (1973) calls *theoretical models* or *specific theories*.

A theoretical model is a hypothetico-deductive system concerning a model-object. Theoretical models can be obtained by embedding a model-object into a theoretical framework or *general theory* (such as classical mechanics, electromagnetism, wave theory).

For instance, in trying to understand the behaviour of a gas confined in a container, we must first have an idea about this gas, that is a model-object. We can imagine the molecules of the gas as point masses colliding with one another and with the container's walls. In addition, we can abstract the energy variations of the molecules, as well as any electromagnetic interactions between them. Through these idealizations and abstractions, we create a model-object to conceptually represent the gas; in this case, it is usually called an "ideal gas". But this alone does not supply us with a theoretical model. When conjoined with a general theory such as classical mechanics, or other general assumptions, is it possible to develop an explanatory theoretical model (e.g. the kinetic theory of an ideal gas). This model allows us to establish relations between the variables of this system and to make predictions about its behaviour, thus building a modest, but fruitful portion of scientific knowledge.

Constructing different models for the same physical situation or object is possible either by creating different model-objects or by adopting different general theories. If we take the volumes and intermolecular forces of molecules into account, for instance, we have another model-object for the gas. Now, embedding this idea in the same general theory as before, it is possible to obtain a new theoretical model, namely van der Waals' model. Inversely, we could have adopted another general theory (e.g. relativistic dynamics) and conjoined it with the ideal gas model as a model-object to obtain yet another theoretical model for the gas' behaviour. This is how models are partially independent from both theory and data and hence consist of relatively autonomous agents, as pointed out by Morgan and Morrison (1999).

Any theoretical model inherits the partial and idealized character of the model-object. This means that we should not expect any model to mirror reality. Instead, theoretical models are tentative by nature, and they can agree approximatively with empirical evidence at best. On the one hand, they are far richer than the model-object due to their explanatory potential. On the other hand, they are much more open to scrutiny than general theories, which cannot be empirically tested. Therefore, theoretical models can be seen as mediators between theory and our ideas about reality (Bunge 1963). But these models might have different explanatory potentials, according to distinct approaches that might be taken in order to construct them.

4 Black boxes and Mechanisms

Bunge (1973) considers the most superficial kind of models as corresponding to the *black-box approach* (also called *phenomenological* approach), the aim of which is to describe and predict the behaviour of a system. Black boxes are constructed by relating input variables to output variables, without further consideration of possible internal mechanisms. They provide concise and global, although simplistic, representations of the system being modelled. Some examples of this approach are the following: *kinematics*, the analysis of motion without considering forces; *geometrical optics*, which does not inquire about the "internal structure" of the light; and the *behaviourist theory of learning*, which is based on the principle of stimulus–response.

Symbolically, the representation of any black-box model may take the form $O = MI$, wherein "I" is the input variable or initial state, "O", is the output variable or final state, and "M" would be an intervening variable, operator, or function. What characterizes a model as a black box is not that it denies the possibility of an internal mechanism, but that it does not hypothesize one and usually considers the intervening variable as a computational auxiliary. Thus, black-box building may be seen as a view of the system "from the outside", and it is frequently (but not always) employed in the initial stages of scientific theorization development about a given subject (Bunge 1998).

Because they are more closely related to experimental evidence and more superficial at the same time, black boxes tend to be relatively more difficult to refute. For instance, Ohm's law relates the current passing through a conductor with the potential difference across this conductor. This theoretical model was initially developed experimentally by Georg Ohm using a thermocouple and a galvanometer. It provides a relation between the chosen variables, but it does not explain why the relation is as stated. Also, it is approximate by nature, as the relation holds only at constant temperature, which is not strictly possible, especially because of Joule heating effects. In light of this example, it can be seen that black boxes do not deal only with macroscopic or directly observable variables, as currents and electromotive forces do not fit in this category.

By contrast, there are translucent boxes (or representational approaches) that attempt to understand the internal mechanism of a system or event. This mechanism is hypothetical, and it is invented using unobservable and abstract concepts. Also, between black boxes and translucent ones, there are intermediate, semi-translucent approaches. In these models, the intervening variable M contains the explanation of the internal mechanism of a system (Bunge 1974). Also, it should be noted that both theoretical models and general theories can be associated with any kind of boxes, since this categorization refers to an approach and not a scope or a reference.

The construction processes of translucent or semi-translucent boxes are not required to be separated from black boxes by starting all over again, but instead they might be elaborated upon using the black box as a first step or initial foundation. McMullin (1985) refers to this process as a "de-idealizing" technique, and he exemplifies it with the sequence of historically developed models for the hydrogen atom. Bohr's initial model postulated a massive proton at rest with an electron in a circular orbit around it. Later, the model was refined by allowing a small motion of the nucleus around the common centre of gravity. Afterwards, the orbit was assumed to be elliptical, and, later on, relativistic effects were taken into account. This successive refinement and addition of complexity becomes progressively more dependent on constructs (e.g. centre for mass) and theories (e.g. special relativity). Portides (2007) made a similar claim and stated that progressive de-idealizations provide an approximate representation of the target physical system.

Thus, for the purpose of building translucent or semi-translucent boxes, it is necessary to create more abstract, non-observable constructs through abstractions and idealizations. In addition, it requires taking into account the role of general theories in the model construction process. In the case of electrical conduction, for instance, if current is modelled by a certain distribution of electrons moving through a medium with scattering centres (ions from the conductor's structure) and this model-object is connected with classical mechanics and electrodynamics as general theories, it follows that current density is proportional to the electric field, which is a reformulated version of Ohm's law, the new consequent theoretical model.

This example illustrates a few points about translucent boxes. Firstly, the constructs needed to develop an explanation for the system's "internal mechanisms" must not be seen or measured, but imagined and invented: electrons, crystalline structures, fields, potentials, all of them are highly abstracted model-objects. Secondly, general theories are important not only as a means of deriving the model but especially as ways of assigning factual meanings to intervening variables, therefore bringing up interpretations for the inner structure of the system or object being modelled and fostering deeper explanations. In this specific case, resistance can now be a property that is physically interpreted in terms of the conductor's structure, instead of simply being a constant that relates input and output. Of course, other model-objects might have been (and indeed were, throughout history) created to represent current in a conductor; also, other general theories might be adopted in modelling its functioning. Again, this illustrates the relative autonomy of a theoretical model and its role in mediating between a theory and the objects to which the theory is supposed to relate. One last remark has to be made about translucent boxes: by allowing the model to be integrated into a wide-ranging theoretical structure, it is no longer something apart from the rest of the science, as it is the case for black boxes (Bunge 1973).

Although black boxes are considered by Bunge to be necessary, especially when facing a new problem, he also regards them as insufficient for the reasons discussed above. To him, the long-term goal of science is to explain reality and not just to accumulate data. Therefore, constructing translucent boxes is highly desirable in scientific enterprise and should be encouraged. Besides, in order to develop explanations for the internal mechanism, gathering more and more data will not be of any help. This goal can only be achieved through an inventive effort using the subject's imagination.

At this point, we are able to see more clearly how idealization and abstraction help create scientific explanations, as pointed out by McMullin (1985). Both these processes are required in order to build less opaque, more greyish or translucent boxes, which in turn provide models with higher explanatory power (Bunge 1973). However, that does not mean that building black boxes is easier or that it does not require creativity and imagination. Actually, a great deal of abstraction and idealization is required even to develop this kind of model. This is very clearly seen when we look at Galileo's *Dialogues*.

5 A Model-Based View on the Galilean Studies

Taking a cognitive–historical perspective, Palmieri (2003) addresses Galileo's mathematization of nature in terms of underlying cognitive mechanisms. An important point raised by the author regarding the acceptability of Galileo's thesis during its own time is his use of visual representation as a substitute for propositional construction as a means of proof. After analysing one of the most famous Galileo's thought experiments, concerning the free fall of heavy bodies, Palmieri (2003) suggests that Galileo tackled the issue by means of a model-based reasoning in order to develop his mathematization of the world. Even though we do not use the same framework for the modelling process as Palmieri's, in the following pages we will argue that Galileo did develop his new science strongly supported by a model-based view of nature, in particular, by shifting the reference of theories from sensible objects to conceptual objects.

Abstractions and idealizations appear as distinctive marks in the Galilean studies. It is possible to identify the extensive use of these thought processes in most, if not all, of Galileo's seminal works. His famous argument that different bodies would fall with the same speed in a medium without resistance is an example of this type of reasoning, since there can be no such medium in any real situation. Thus, his proposition refers to an abstract construct. Another example can be taken from his discussion about the levers' operation: trying to demonstrate how a lever can be used to lift a very heavy stone, Galileo deals with the question of "treating the lever as an immaterial body devoid of weight" (Crew and de Salvio 1914, p. 113). This "immaterial body" proposed by Galileo is clearly an idealized construct intended to represent a real object. Therefore, it can be considered a model-object.

Similarly, idealizations and abstractions appear explicitly in the problem of the ball dropped from the mast of a moving ship. In order to convince his interlocutors that the ball lands at the base of the mast, Galileo referred to his principle of inertia, using the motion of an object dropped on the inclined plane as an example:

> Notice that I am referring to a perfectly round ball and a fastidiously polished plane, in order to remove all external and accidental impediments; similarly, I want you to disregard the impediment offered by the air through its resistance to being parted, and any other accidental obstacles there may be. (Finocchiaro 1997, p. 166).

Since these are impossible conditions to be met, either because they imply omitting existing "impediments" or simplifying objects, this passage also illustrates how Galileo used these two processes (i.e. abstractions and idealizations) to produce model-objects, that is ideas about objects he was studying: frictionless planes, perfectly spherical balls, media without resistance, and so on. Then, he developed theorizations, models, and predictions based on these model-objects and using them as references.

But Galileo recognized that his description of reality did not correspond directly to the natural world. When he was talking about projectile motion, he described geometrically this motion as a combination of a horizontal component (transverse motion, which is uniform) and a vertical component, which is the "natural" descending motion. Then, he showed that the result of this combination is a parabolic trajectory. Both his interlocutors questioned him, pointing out what they saw as inconsistencies in Galileo's explanation, especially regarding the idea that the horizontal component would be a straight line and the act of ignoring resistive effects of the medium. Galileo's answer showed how aware he was about the approximate character of his own models:

> All these difficulties and objections which you urge are so well founded that it is impossible to remove them; and, as for me, I am ready to admit them all […] I grant that these conclusions proved in the abstract will be different when applied in the concrete and will be fallacious to this extent, that neither will the horizontal motion be uniform nor the natural acceleration be in the ratio assumed, nor the path of the projectile a parabola, etc. (Crew and de Salvio 1914, p. 251).

The very mathematization of Galileo's ideas about reality that he used in order to geometrize experimental arrangements as well as to identify the trajectories of bodies with certain types of curves can also be interpreted as a form of idealization and model constructing. This can be clearly seen in Galileo's discussions about the pendulum problem, as in the Fourth Day of *Dialogues Concerning Two Chief World Systems*. In this essay, Galileo derived the regularities assigned to simple pendulum motion mainly by using the idealizations he had previously presented, as neglecting resistive effects, and by depicting physical circumstances geometrically, such as identifying rods with straight lines and the bob's trajectory with arcs.[2] Thus, it is possible to see that the predicates that Galileo assigned to objects were hypotheses that form a model-object, in this case, the simple pendulum.

[2] This line of reasoning, based on representing physical variables using geometrical objects, can be found in Galileo since his earlier studies about pendulums, as in the work *On Motion* (1590) and the letters he exchanged with his patron Guidobaldo del Monte (1545–1607).

Addressing the pendulum motion again, now through an experimental reasoning in *Two New Sciences*, one of the conclusions he derived is the law of length: the period of a simple pendulum (output variable) is proportional to the square root of its length (input variable).[3] This is a theoretical model relating one of the variables of the pendulum to another, without inquiring why the relation obeys this particular functional form. On commenting on this law, Galileo proposed to reverse the black box; that is, he pointed out the possibility to determine the length of an unknown pendulum by measuring its period. Additionally, he indicated that this procedure is fairly precise, especially when counting many oscillations. It is interesting to notice that, when commenting on black-box approaches, Bunge (1973) indicates exactly these two issues—prediction and reversed prediction—as the two basic problems that can be solved by this kind of model.

At least two more models created by Galileo concerning a pendulum's motion follow a similar line of reasoning. One of them was the law of weight independence that states that the pendulum's period (output variable) is independent of its weight (input variable).[4] The other, pursued at length by Galileo throughout his career, was the law of isochronism, which states that, for a given pendulum, all oscillations take the same time (output), no matter the amplitude (input).[5] At different stages in his works, Galileo treated the pendulum as a highly idealized system made of geometrical components; therefore, he established a model-object, or as an experimental setting, with which he attempted to create theoretical models.

Similarly, when analysing accelerated motion in the inclined plane, Galileo varied, for example, distances travelled by a body (input variable) measuring the time elapsed (output variable). In the Third Day of *Dialogues Concerning Two New Sciences*, he concluded by stating a model for the motion of a body on an inclined plane, that is the idea that the

[3] "Suspend three balls of lead, or other heavy material, by means of different lengths such that while the longest makes two vibrations the shortest will make four and the medium three; this will take place when the longest string measures 16, either in hand breadths or in any other unit, the medium 9 and the shortest 4, all measured in the same unit. Now pull all these pendulums aside from the perpendicular and release them at the same instant; you will see a curious interplay of the threads passing each other in various manners but such that at the completion of every fourth vibration of the longest pendulum, all three will arrive simultaneously at the same terminus, whence they start over again to repeat the same cycle". (Crew and de Salvio 1914, p. 107).

[4] "Accordingly I took two balls, one of lead and one of cork, the former more than a hundred times heavier than the latter, and suspended them by means of two equal fine threads […] the heavy body maintains so nearly the period of the light body that neither in a hundred swings nor even a thousand will the former anticipate the latter by as much as a single moment, so perfectly do they keep step". (Crew and de Salvio 1914, p. 84).

[5] "Attach two threads of equal lenght—say 4 or 5 yards—two equal leaden balls and suspend them from the ceiling; now pull them aside from the perpendicular, the ont through 80 or more degrees, the other not more than four or five degrees […] if two persons start to count the vibrations, one the large, the other the small, they will discover that after counting tens and even hundreds they will not differ by a single vibration, not even by a fraction of one". (Crew and de Salvio 1914, pp. 254–255). It should be noted that, in the situation described here, it would be easy to verify that the two pendula would desynchronize very rapidly, since the pendulum period increases with amplitude. Only for small amplitudes the period is independent of the initial angular displacement: it is an approximation. As he refers to 80 degrees or more, Galileo most likely never did this experiment, even though he presents it as an experimental result. This indicates that even to develop black-box models, which are considered the more superficial and closer related to experimental evidence, the epistemic subjects' theoretical commitments still play a very significant role. By the same token, in actual modelling practices, including educational ones, what subjects consider to be observational facts tend to be influenced by their own expectations and conceptions.

spaces traversed were proportional to the squares of the times.[6] Galileo presented this relation initially through geometrical reasoning, but structured in propositional form, as it was proper for his time. Further in the *Dialogue*, he dealt with the question of whether this relation applies to nature, by describing an alleged experiment intended to test it: a round bronze ball is placed in a channel cut in a wooden moulding, and its descending time is measured using a sort of water clock. He was extremely mindful to describe this groove as "very straight, smooth, and polished" and the bronze ball as "hard, smooth and very round".

While still dealing with the inclined plane, Galileo proposed many other similar relations between variables, concerning varying quantities as well as constant ones. For instance, he compared the speeds with which a body reaches the bottom of a plane, according to different inclination angles, claiming that they are equal; he stated that the length of any inclined plane and of a vertical line with the same height bore to one another the same ratio as the times of descent of the same body, starting from rest, along each path, and so on. In all of his propositions and theorems throughout the book, it is possible to identify clearly stated and extensively argued relations between variables of highly geometrized (i.e. abstract) systems.

Therefore, in the case of the inclined plane, as well as in the pendulum problem, we can interpret Galileo's models as black-box models. Although he himself did not adopt an algebraic approach, these models can be schematically represented by relations like $\Delta x = Mt^2$ and $T = M\sqrt{l}$, respectively, for the inclined plane and the pendulum motion. In both these relations, the intervening variable M does not receive a physically interpreted meaning, since Galileo did not create hypotheses about why the bodies move the way they do. Galileo himself made explicit his option for not discussing the causes of acceleration, in the Third Day of *Two New Sciences*:

> The present does not seem to be the proper time to investigate the cause of the acceleration of natural motion concerning which various opinions have been expressed by various philosophers […] Now, all these fantasies, and others too, ought to be examined, but it is not really worthwhile. At present it is the purpose of our Author mere to investigate and to demonstrate some of the properties of accelerated motion (Crew and de Salvio 1914, p. 166).

6 Teaching Implications

Analysing Galileo's studies in the light of Mario Bunge's ideas about the modelling process made it possible to express more clearly a strong feature in Galileo's work: the fact that his ideas do not refer to real objects, but rather to constructs. This seems to be one of the major factors of disagreement between him and other natural philosophers of his time. Galileo shifted the reference of scientific theorizations, from sensible objects to idealized and abstract concepts of these objects, that is model-objects. In addition, and lacking a general theory for dynamics, Galileo's works on mechanics focused on examining specific situations or systems, for which he developed specific models. These models are constituted mainly by relations between chosen variables of an idealized, abstract version of the targeted situation. Although some considerations made in the context of a particular problem are sometimes transported to the analysis of another (e.g. the idea of a

[6] "Theorem II, Proposition II: The spaces described by a body falling from rest with a uniformly accelerated motion are to each other as the squares of the time-intervals employed in traversing these distances" (Crew and de Salvio 1914, p.174).

combination of horizontal and vertical components to produce a resulting motion), there is no comprehensive theoretical principle by means of which it would be possible to deduce Galileo's models. Thus, his studies can be interpreted as the construction of black-box models.

Black boxes are useful when underlying mechanisms are not sought for the time being, "…either because of an anachronistic methodological conviction or because the grapes are still sour" (Bunge 1963). The latter can be the case of many science students, especially in introductory courses such as elementary and secondary education. In this sense, having black boxes as starting points for constructing scientific theorizations in the classroom may have at least three relevant contributions. One of them is the possibility of rendering explicit the conceptual character of objects with which science directly deals. This feature is very clearly stated in Bunge's concept of the model-object. Making it explicit may help students develop a more reflective understanding about the relation between scientific knowledge and the world it intends to explain, as well as recognizing what justifications underpin abstractions and idealizations as legitimate ways of scientific reasoning. Another contribution of black-box construction in science teaching is to make it possible to recover its conceptual context: in dynamics, for instance, the fact that was initially based on some previous knowledge about a few particular kinds of motions (e.g. the ones studied by Galileo) meant that it was possible to develop highly abstracted theories with a much larger scope (e.g. Newton's dynamics). In other words, the knowledge given by one or more black boxes helps to assign meaning to the contents of general theories. A third contribution of this approach is to allow exploration of the approximation aspect of scientific models in an explicit and clear way, through its mediating character. By serving as a bridge between theories and the empirical domain, black boxes enable both students and teachers to question and argue about the ways in which scientific theories do represent the world, and the ways they do not.

In this context, the problem exposed in the first two paragraphs of Introduction can be reformulated as follows. Typically, teaching practices in physics classrooms tend to present model-objects already in the beginning, without explicitly describing the real objects this model intends to represent, in what ways the former represents the latter, and in what ways they are different from one another. This leads students to confuse them and to believe that theories refer immediately to real objects. On the other hand, general theories are usually taught before theoretical models, which are presented as direct applications of general theories in a purely deductive way. This is not just misleading, as it omits the need for the model-object to articulate between general theory and theoretical model, but it also misses the opportunity to explore the approximate and idealized character of scientific knowledge.

As it has been developed here, the didactical use of the history of science can offer an alternative way for implementing modelling goals in the classroom, by making it possible to discuss different model-objects, theoretical models, and general theories created by philosophers and scientists through time, in their attempts to explain nature. In particular, Galileo's works seem to be especially fruitful for pursuing this aim, since they arise within the birth of modern science. The invention of model-objects through idealizations and abstractions is made explicit in his *Dialogues*, along with the processes of creating, testing, and critically evaluating theoretical models.

Developing a modelling in the classroom, in the light of Mario Bunge's epistemology, could be understood as a gradual transition from more "unrefined" situations, which were not yet fully abstracted and idealized, towards more representational situations. This could be done by creating black boxes that, through the teacher's mediation and introduction of the general theories, may increase the "amount of light" that traverses the box over time.

Our purpose was to indicate that, along with experimental activities and mathematical skills, history of science can also constitute an alternative method to foster modelling practices in the classroom. In particular, we emphasize that the didactic use of Galilean studies can be a potentially fruitful strategy to help overcome the separation between scientific theories and reality in science education.

7 Concluding Remarks

As Segre (1980) points out, it would make no sense to expect strong epistemological consistency when analysing the work of Galileo, as he himself made few methodological remarks and did not seem to follow the same *modus operandi* throughout his life. Most, if not all, essays attempting to interpret the works of Galileo are likely to be highly influenced by their own author's epistemological convictions. Therefore, our interpretation of Galileo as a black-box constructor does not imply any intention, consciousness, belief, or theoretical commitment from his part with this methodological option. By the same token, this interpretation is not intended for any historical purposes, but rather exclusively for teaching ones.

Moreover, some clarifications are necessary in order to avoid misunderstandings. First of all, although the course from simplest models to more complicated ones might seem natural, it is not necessarily the historical one, since there is no deterministic path for scientific development. In addition, the account of the modelling dynamics presented here is definitely not a comprehensive account about how science develops. For instance, it does not focus on the process of general theories production, in the form of wide paradigmatic changes, and it also does not deal directly with non-epistemic factors that influence scientific knowledge construction. Instead, it provides a model of models, i.e. an approximate attempt to explain some important features about scientific models, intended for science education aims. In this sense, this proposal cannot account for all of the details and complexities of scientific models. Nevertheless, it does point out how the modelling process in the classroom might help students to critically improve their understanding of the relation between reality and theory in scientific knowledge construction—and how the history of science might help to reach this goal.

Compliance with ethical standards

Conflict of interest The author declares no conflict of interest.

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