Making Sense of Models and Modelling in Science Education: Atomic Models and Contributions from Mario Bunge’s Epistemology

Juliana Machado[1]

Abstract—Conceptions about the nature of scientific models held by science students frequently involve distorted views, with a tendency to consider them as mere copies of reality. Besides encompassing an untenable view about the nature of science itself, this misconstruction can effectively be a pedagogical impediment to learning. **Objectives**: We evaluate whether Mario Bunge’s epistemology might contribute to tackling issues related to the nature of models in science education contexts. **Design**: After identifying Bunge’s main model categories, we employ them to examine aspects of the historical development of atomic models and contrast the resulting framework with issues about model conceptions in science education, as pointed out in the literature. **Setting and participants**: Due to this research’s theoretical nature, this study did not include human participants other than authors from the literature and the theoretical framework. **Data collection and analysis**: We performed a constant comparative analysis to identify patterns of meanings shared between the historical case and the theoretical framework. **Results**: Features of models pointed out by Bunge were identified in the development of atomic models and could provide consistent and explanatory viewpoints about key issues related to model conceptions in science education. **Conclusions**: Bunge’s framework might help to clarify aspects of the nature of models relevant to science education contexts.

Résumé — Les conceptions que les étudiants en sciences ont de la nature des modèles scientifiques conduisent à une image inexacte de ceux-ci, notamment lorsque les modèles sont vus comme de simples copies de la réalité. Outre le fait qu’elle entretient une conception fausse de la nature de la science, cette façon de se figurer les modèles peut constituer un obstacle pédagogique à l’apprentissage.

[1] **Juliana Machado** holds a degree in Physics (2007) and a Master's degree in Science and Technology Education (2009) from the Federal University of Santa Catarina, as well as a Ph.D. in Science, Technology and Education from the Federal Center for Technological Education "Celso Suckow da Fonseca" (2017). She is a professor and researcher at the Graduate Program in Science, Technology and Education (PPCTE) of CEFET/RJ.

Objectifs : Nous évaluons l'épistémologie de Mario Bunge afin de déterminer si elle peut contribuer à résoudre les problèmes liés à la nature des modèles dans un contexte d'enseignement des sciences. **Approche** : Après avoir identifié les principales catégories des modèles chez Bunge, nous les employons pour examiner divers aspects du développement historique des modèles atomiques, puis nous appliquons le cadre théorique ainsi obtenu aux problèmes liés aux diverses conceptions des modèles en enseignement des sciences. **Participants** : En raison de la nature théorique de cette recherche, cette étude ne fait pas appel à des participants autres que les chercheurs des recherches mentionnées. **Collecte et analyse des données** : Nous avons effectué une analyse comparative constante afin d'identifier les schémas de signification communs au cas historique et au cadre théorique. **Résultats** : Les caractéristiques attribuées aux modèles par Bunge ont été identifiées dans le cas des modèles atomiques. Ces caractéristiques forment un point de vue cohérent et permettent d'aborder, dans le contexte de l'enseignement des sciences, plusieurs questions liées aux diverses conceptions des modèles.

Keywords—Models, Modelling, Epistemology, Nature of Science, Atomic Models.

The value of models and modelling in science teaching has long been recognised in the literature. Despite their widespread use, researchers have a variety of viewpoints on the nature of models. This paper does not deal with this plethora of model conceptions. Instead, we turn to one specific view about models and modelling, potentially fruitful to deal with issues in science education, such as their idealized and abstract character, and we discuss its implications in interpreting an important sector, that of atomic models.

To reach this aim, in the following pages, we firstly provide a context to describe the issues above-mentioned, after which we present Mario Bunge's framework for the analysis of models and modelling, which gives special attention to the relationship between scientific knowledge and reality. Subsequently, we deepen the discussion about abstractions and idealizations, which are at the core of that relationship. Then we employ these ideas to interpret aspects of the development of atomic models, from J. J. Thompson to A. Sommerfeld. Finally, we discuss teaching implications, showing how Bunge's framework helps to clarify aspects of the nature of models relevant to science education contexts.

1] Background

In his critique of the Nuffield project, then just recently published, Gebert (1969) appeals only to his own teaching experience to state that, in general, secondary school students are not able to understand and work properly with models, mainly because they see them as “physical realities”. By attributing this fact to student immaturity and fearing that early modelling will have detrimental effects on learning, Gebert (1969) proposes to avoid the topic altogether until students reach an age where they can properly understand it—which would happen, according to the author, around the age of 17 or 18.

Gebert’s (1969) diagnosis has been consistently confirmed by science education research: it seems that students tend to understand models more as copies of reality than as conceptual, partial, and approximative representations. However, the treatments that have been proposed to address this problem diverge from the suggestions of Gebert (1969). Grosslight and colleagues (1991), for example, interviewed students in the seventh and eleventh grades of compulsory schooling in the United States to investigate their conceptions of models and highlighted—as did Gebert (1969)—the difficulty presented by both groups in distinguishing scientific models and realities they are supposed to represent. Rather than proposing to abandon teaching with models, the authors offered three suggestions: (1) to provide students with intellectual problems that require the use of models; (2) to explore multiple models for the same phenomenon by modifying and revising them; and (3) to invest some didactic work in metaconceptual reflection on the nature of the models.

Regarding the possible causes for the symptoms highlighted by Gebert (1969) and others, Harrison and Treagust (2000) pointed out reasons for students’ lack of understanding of the nature of science and of the scientific content itself. One point emphasised by the authors is the absence of discussions about the representational character of scientific models in textbooks, which can be extended to classroom educational practices: usually, discussions about the nature of the models and their use, and opportunities to develop provisional models and assess them, remain absent in teaching situations (Gilbert & Osborne, 1980). This may be partially due to the teacher’s difficulties distinguishing the scientific model from the modelled object or event (Coll et al., 2005). Thus, the school curriculum traditionally neglects the approximative character of the models, tending to present them as mere copies of reality (Lefkaditou, Korfiatis & Hovardas, 2014).

Consequently, it is possible to understand students' perplexity when models of the same phenomenon are presented throughout the educational process, one after the other. If the scientific model holds a one-to-one correspondence with its object, there could not be multiple valid models for the same phenomenon. Therefore, students assume that the most recently studied model must be the "correct" one, which naturally frustrates students who have dedicated efforts to learn the "wrong" models in earlier stages of schooling. This distorted character of scientific knowledge is not only epistemologically misconstrued but can also be a pedagogical impediment to learning (Taber, 2012).

So, contrary to Gebert's (1969) suggestions, models are currently regarded in science education contexts as constructs to be used and understood by scientists and students as an integrated part of their learning processes. These processes include learning science's contents, practices and nature (Hodson, 2014). However, there is no single, universally accepted definition of a scientific model, but several distinct understandings (Krapas et al., 1997; Machado & Fernandes, 2021), mostly influenced by ideas drawn from psychological and philosophical frameworks (Justi & Gilbert, 2016).

2] Theoretical Framework

Mario Augusto Bunge (1919-2020) was an Argentine-Canadian philosopher and physicist who wrote or edited around 80 books and 500 scientific or philosophical papers. As he was a scientific philosopher and a philosophical scientist, Bunge's prodigious academic output was always committed to studying the interaction between science and philosophy and defending the best of both. Teaching first physics and philosophy at the Universities of La Plata and Buenos Aires during the 1950s, Bunge also taught those subjects in the USA during the early 1960s. In 1966, he was appointed professor of philosophy at McGill University in Montreal, where he became Frothingham Professor of Logic and Metaphysics until his retirement at age 90. Besides always being a socially engaged intellectual—even founding a college for workers, *Universidad Obrera Argentina*—, Bunge played a key role in giving international relevance to Latin American philosophy. In an international philosophical congress held in 1956 in Santiago (Chile), he was particularly noticed by Quine, who later wrote in his autobiography:

> The star of the philosophical congress was Mario Bunge, an energetic and articulated young Argentinian of broad background and broad, if headlong, intellectual concerns. He seemed to feel that the burden of bringing South America up to a northern scientific and intellectual level rested on his shoulders. He intervened eloquently in the discussion of almost every paper. (Quine, 1985, p. 266)

In a book published in 1959, *Causality*, Bunge criticized the empiricist conception of causality and developed a realist account of it. The book soon gained international recognition and marked a turning point, because after its publication, " … books one may call 'classics' were now coming out of Latin America and finding a place in mainstream reading lists in the English-speaking world and Europe" (Lombardi et al., 2020)

Being a realist, Bunge sees scientific models as fundamental entities in the quest for conceptual understanding of reality. They would play the role of mediators, similar to the one proposed later by Morgan and Morrison (1999), between reality and the theories that deal with it. But what does "reality" mean in this context? The concept of reality maintained by Bunge consists of the aggregation of all things that hold spatiotemporal relations with each other: "The reality of an object consists in its being a part of the world" (Bunge, 1977, p. 161). In other words, a "real thing" in the context of physical knowledge would be the intended referent of a physical theory (Bunge, 1977).

This definition leaves out conceptual objects, such as scientific constructs. These are not endowed with reality, although they do exist conceptually. In addition, Bunge emphasises that reality is not reducible to observation, since it postulates the existence of unobservable entities such as waves and forces, let alone to experiment, because it accepts components that cannot be extracted from the latter, such as electrons and inertia (Bunge, 1973a). Finally, to him, the reality is changeable, i.e., there are possibles that may not yet be actualized. Thus, reality can be divided into two classes: actualities and real possibilities (Bunge, 1977).

Bunge claims that science does search for reality, but can never attain it perfectly or completely, only approximately. This means that scientific knowledge does make actual progress in its quest, even though never fully accomplishing it. The author expresses such an idea, which is characteristic of critical realism:

> […] things in themselves are knowable, though partially and by successive approximations rather than exhaustively and at one stroke […] this knowledge (factual knowledge) is hypothetical rather than apodictic, hence it is corrigible and not final… (Bunge, 1973b, p. 86)

As a result, Bunge dismisses both scepticism and dogmatism, claiming that incremental and tentative access to knowledge is feasible, thereby subscribing to a perspective on the problem of knowledge's possibility known as criticism (Hessen, 1997; Niiniluoto, 2002). Furthermore, the author expresses his support for ontological realism, a viewpoint that refers to the essence of knowledge and is opposed, for example, by the Vienna Circle's logical positivists (Niiniluoto, 2002).

Little has been stated on the problem of knowledge's origins thus far. Bunge (1973a) opposes rationalism and empiricism, claiming that neither reason nor experience can be the single or primary basis of scientific knowledge (Bunge, 1985). Bunge also argues that our knowledge of reality is something we create, by stressing that theories and models do not have reality as an immediate reference, but rather conceptual versions of real objects, invented by the epistemic subject: "Epistemological constructivism is correct, but the ontological one is false" (Bunge, 1991, p. 51).

2.1] Concepts of Model

In trying to elucidate the relation between reality and scientific knowledge, Bunge pointed out that such knowledge does not refer directly (or immediately) to real objects and events. This reference is mediated by constructs, which he called "model objects" (Bunge, 1973a). These consist of conceptual representations of the targeted real objects. For instance, a fluid can be represented by a continuum possessing specific attributes, such as viscosity and compressibility. Such model-object will inevitably

> […] miss certain traits of its referent, it is apt to include imaginary elements, and will recapture only approximately the relations among the aspects it does incorporate. In particular, most individual variations in a class will be deliberately ignored and most of the details of the events involving those individuals will likewise be discarded". (Bunge, 1973a, p. 92)

All fields of mature natural sciences, claimed Bunge, are full of model objects. So, for instance, physics has mass points, light rays, ideal threads, photons, Carnot heat engines, and so on; chemistry has, e.g., atomic models, pure substances, ideal gases, orbitals, molecular models, valence shells; and biology encompasses model objects such as cells, species, genes, Watson and Crick's DNA model, among many others. It is also possible to develop different model objects to represent the same referent: for example, we can model the Moon as a point mass, as a sphere or as an oblate spheroid, homogeneous or non-homogeneous in each case. These would all be distinct constructs, with different degrees of approximation, but none would be identical to the actual Moon, because epistemic subjects create model objects through idealizations and abstractions, thus modifying the objects' aspects to a certain extent.

An important distinction between model objects and real objects is that the former are ideas, while the latter are things. This property makes model objects able to be grafted onto theories, unlike real ones. More appropriately, Bunge used the term "general theories" to allude to wide-ranging theoretical frameworks, potentially applicable to all phenomena under its domain, e.g., classical mechanics and electromagnetism. When embedding a model object in a general theory, we can create theoretical models, i.e., hypothetical-deductive systems concerning the model object. Unlike the model object and the general theory, theoretical models have explanatory power, which can be used to make predictions about the targeted system and to establish relations among its variables, as well as being subjected to empirical testing.

Bunge explains that any model object can be implanted into different general theories, thus forging different theoretical models. For example, the ideal gas can be combined with classical or relativistic mechanics, bringing forth two different theoretical models for the gas. Reciprocally, varied model objects (concerning the same real object) may be inserted in a single general theory to engender distinct theoretical models. An example could be to replace the ideal gas for Van der Waals's model.

All philosophers, including Bunge, concur that general theories alone cannot be tested. This is due to the fact that, precisely by their generality, they do not make any specific prediction without having more hypotheses or auxiliary statements (or model objects) added to them. Thus, they do not generate, by themselves, propositions which could be compared to actual empirical data (theoretical models). Another way to put it is to consider that any general theory may produce an infinite number of predictions of the same situation, according to the specific hypotheses that would be added to them. Conversely, empirical refutation of a given theoretical model does not imply the refutation of the general theory that took part in its construction (if there was any). In short, general theories can be supported or weakened by testing their theoretical models, but cannot be proved or refuted conclusively (Bunge, 1973a).

2.2] Throwing Light Into Our Models

In some cases, there is simply no general theory available at the time when scientists are trying to develop new theoretical models in their fields. This was the case when Galileo was undertaking his famous works in mechanics. Working before Newtonian synthesis and against Aristotelian dynamics, Galileo did not have any comprehensive theory on which to root his propositions. That did not stop him from creating many theoretical models, though. What Galileo did was to search for and establish relations among variables—distances, times, speeds, lengths, periods and so on—in different experimental or imaginary settings, while suspending judgment on why the relations were that way. This is an example of what Bunge called black box models. Black boxes relate input and output without allowing us to see the "internal mechanism" responsible for such a relation. Boyle-Mariotte's law, geometrical optics and classical behaviourism are also examples of models following this approach. Even if they are, in some sense, more superficial than other approaches, black box models also extensively use abstractions and idealization. In particular, the case of Galileo's models was the object of many studies in this regard (e.g., McMullin, 1985; Palmieri, 2003; Machado & Braga, 2016).

Black boxes are useful, important, and fruitful, especially in the beginning stages of modelling, but they have low or no explanatory power. To foster deeper explanations requires letting more light traverse the box, meaning searching for its inner structure and mechanism. In so doing, we would be constructing translucent boxes, which can be done with the help of general theories. Translucent boxes help promote deeper explanations and connect the new model to the rest of our knowledge, avoiding its isolation. However,

> […] in general, whether we have to do with light or with chemical bonds, with thought or with institutions, the task is hard and probably open-ended. The reason for this is that most of the structures

> and mechanisms responsible for appearance are hidden to the senses. Hence, instead of attempting to see them we must try to imagine them. (Bunge, 1973a, p. 103)

Our daily lives are full of black boxes. Bunge exemplifies this fact by noting that a car is a black box to most drivers, in that they operate levers and switchers predicting successfully what these will do, without any knowledge about how engines or transmission mechanisms work. Yet to the mechanical engineer, the car is more like a translucent, perhaps almost transparent box. In concluding this brief synthesis of the Bungean box approach, it is necessary to emphasise that it is not a question of framing all possible approaches in one or the other extreme (black box or translucent box), but of realising that these approaches are distributed in a continuum, in which the intensity of light that passes through the box varies according to the research objectives and the contexts within which it takes place.

3] Idealization and Abstraction in Scientific Models

In the previous section, the concepts of idealization and abstraction were pointed out as thought processes performed by the epistemic subjects to create model objects. However, what are idealizations and abstractions? How do they take part in creating scientific knowledge? In what follows, we discuss some of the contributions of philosophy of science to such and related problems and situate Bunge's view in this context.

Suppe (1989) defines the selection of which variables and parameters of the real object are to be considered in the models as a process of abstraction. For instance, in discussing the motion of a pair of bodies under mutual gravitational attraction, one may disregard gravitational forces exerted by other bodies from outside this system. The fact that some aspects are being left aside in the case of this "pure" abstraction does not change the nature of the aspects considered in the model (Suppe, 1989).

But some parameters, when abstracted, produce situations that are impossible for any phenomena to meet. As an example, we can consider the case of point masses in classical mechanics: by ignoring the extension of a body, an object can be modelled as a unique point in space. Of course, this is an impossible condition for any body to satisfy, since it would require infinite density. Making certain assumptions that could never be achieved in a real object is what Suppe calls an idealization. Therefore, in Suppe's account, any case of idealization also involves some abstraction, since it implies ignoring some of the factors that influence the object or phenomena (Suppe, 1989, p. 96).

Similarly, in discussing the relationship between models and reality, Cartwright (1989) proposes two thought processes: idealization and abstraction. The author notes that what the philosophers mean by using the term "idealization" is usually a mixture of the two. For her, in idealization one starts from a concrete object whose inconvenient properties are "rearranged" before attempting to write a law for the behaviour of that object. The paradigmatic example of the idealization pointed out by the author is the inclined plane without friction. On the other hand, abstraction involves the exclusion of specific properties or characteristics that the object possesses, such as the omission of intermolecular forces in the ideal gas model. Therefore, abstraction involves a subtraction, while idealization involves modification (Cartwright, 1989).

While Suppe (1989) emphasised that idealization involves some form of abstraction, since it implies ignoring some influencing factors, Cartwright (1989) states, in a similar perspective, that idealization would be useless if abstraction was not possible. Such considerations indicate that both concepts are closely related. Even though Suppe's, Cartwright's, and McMullin's accounts are not identical, we can see that all of them identify two main processes performed by the epistemic subject: the omission of some aspects—abstraction, for Suppe and Cartwright, or causal idealization, for McMullin—and the simplification of aspects being considered: idealization and construct idealization, respectively. Morgan and Morrison (1999) hold basically the same views as Cartwright. Alternatively, Portides (2013) maintains that abstraction and idealization are actually two different modes of the same thought process, which he calls conceptual control of variability.

Within the context of modelling, Portides (2007) analyses the relationship between notions of idealization and approximation and how they work together to bring models closer to their actual referents. Portides calls "idealization" a fusion of the processes of idealization and abstraction as understood by Cartwright (1983) and Morgan and Morrison (1999). He defines approximation as a process of mathematical simplification of parts or of a whole theoretical description. This is the case, for example, when it is assumed that the intensity of a resistive force is linearly proportional to its velocity, or to its square. The approximation relation would be given by the proximity between the predictions made by these equations and the experimental measurements. Portides (2007) then shows that the logical properties of the approximation are different from those of the idealization.

In this context, one of the functions of idealization is to broaden the generality of our representations of phenomena. Thus, when we speak of a simple harmonic oscillator, we refer to a wide class of objects and not just some pendulums. The idea—or, in Bunge's (1973a) terms, the model object— "simple harmonic oscillator" represents so many objects because it is an idealization of this class of objects, not because it is an approximation, since many pendulums can be subject to very intense resistive forces, so that its behaviour in almost nothing approaches the prediction of a harmonic oscillator.

In his analysis of the representational role of models, Portides (2007) proposes a distinction between ideal models—which would be the class of theoretical models about an object in the form of mathematical structures that can be elaborated following the laws of theory—and concrete models, which would be the class of models proposed to represent the modelled physical system. The concrete models would be the entities that allow capturing the properties and attributes of this system. Ideal models need to be enriched with some concrete models in order to represent some physical system. Portides (2007) then argues, similarly to Morgan and Morrison (1999), that the class of concrete models is beyond theory, so theoretical models are not derived solely from the latter.

Another way of expressing this idea is to point out, as Morrison (2007) has, that models often involve ingredients that are not contained in theories. Thus, it is possible that the same theory leads to different models of the same referent, according to the choice of these "ingredients". This cannot be ignored if one tries to understand the relationship between the model and its referent. In our interpretation, Morrison's (2007) "ingredients" are mainly the model-objects in the Bungean sense. This view coincides with Bunge's in that he conceptualizes and explains such "ingredients" as model-objects and shows how these choices lead to different theoretical models.

Even though Bunge himself does not emphasise the definitions of abstraction and idealization in his accounts for models and modelling, in his *Dictionary of Philosophy* he defines: “A construct or symbol is epistemologically abstract if it does not invoke perceptions” (Bunge, 2001, p. 1). He states that idealization refers to “ … the schematization or simplification of a real object in the process of its conceptual representation” (Bunge, 2001, p. 102). Such definitions are consistent with those described above in that all imply some detachment from the real object, whether by omission or simplification. In this sense, these two thought processes—abstractions and idealizations—take part in the construction of model-objects, as Bunge defined them.

4] Some Connections With Science Education Literature

As shown above, Mario Bunge’s epistemology places models as central elements of scientific practice. Accepting this perspective also leads to considering the centrality of models in science teaching. In fact, science education scholars became more interested in models’ importance in science teaching and learning as the relevance of such entities in cognitive psychology and the philosophy of science became more widely acknowledged. For instance, Taber (2013) stresses the need to recognise the modelling processes that are indispensably at the core of any depiction of student thinking, knowledge, or learning.

In a similar perspective, Schwarz et al. (2017) claim that the main goal of “Developing and Using Models” is to identify and apply specific ideas about theoretical and actual objects, as well as the connections between them, to explain how systems behave. Such an outlook is very akin to Bunge’s theoretical framework, which focuses exactly on these elements: theoretical and actual objects (i.e., model objects and real objects) and in how the relations with each other (i.e., theoretical models) can help us to figure out the world in which we live. According to these authors, modelling should be at the very core of the science classroom precisely because it is at the basis of science’s intellectual efforts, therefore being closely related to our fundamental desire to make sense of the world.

Additionally, Schwarz et al. (2017) raise another interesting point:

> Sometimes we're happy that we can reliably predict the actions of our world, but often we want to know why something behaves the way it does. Knowing why can help us become even better at figuring out what will happen in the future. As we do this, we are searching for underlying reasons and mechanisms that help us make sense of our experience and of the world around us (Schwarz et al., 2017, p. 111).

This passage resonates with Bunge's account of scientific models as opaque or translucent boxes, besides acknowledging that deeper sense-making involves searching for underlying mechanisms (i.e., letting more light pass through the initially black box). In addition, when attempting to explain the essential features of models, these authors claim that "models are distinct from the representational forms they take" (p. 114). This is clear from Bunge's insistence that models are ideas —in a sense, they have to be ideas, not things (as diagrams, equations, pictures, words, and so on) in order to be incorporated into general theories.

The question is, then, how to develop and use models in science teaching contexts to foster sense-making. Many researchers in the field have widely addressed this issue with several different approaches. In general, modelling in science education can be viewed as an effort to explain reality through a creative dynamic in which scientific knowledge serves as a bridging conceptual framework. Some of the most prevalent approaches for implementing modelling in science education typically involve creating analogues and metaphors, using mathematical concepts to structure relations among variables or performing some sort of experimental task. However, history and philosophy of science (HPS) have also been suggested as a potential strategy for discussing models in science education (Justi & Gilbert, 2000; Matthews, 2007).

According to this viewpoint, science instruction can be improved by taking into account scientific models that are pertinent to important curriculum areas. The idea is that if students have a better understanding of how scientific knowledge develops and how historical, philosophical, and technological settings affect that development, they will have a more complete understanding of the nature of science and will be more interested in learning about it (Justi

& Gilbert, 2000). Gilbert et al. (2000) described the issue of modelling in science education in terms of the relations between reality and theory, with models being the mediators. In these authors' opinion, Bunge's framework

> […] is very helpful in that it deals with the relationship between the notions of "model" and "theory" in some detail. The scheme would seem to be applicable to scientific enquiry at any stage in the process of change from the situation (in Kuhn's terms) of "normal science" to that of "revolutionary science". With suitable examples, it should be intelligible to students. (Gilbert et al., 2000, p. 36)

Similarly, Matthews (2007) highlights that being clear about the distinction to be made in science between real things and theoretical objects is a step toward a better understanding of the role of models and theories in science. As discussed in the *Theoretical Framework* section above, such a distinction is a major theme in Bunge's ideas, constituting the very core of the model-object concept. Following Bunge's notions along these lines, Matthews (2007) then advocates for the process of progressively refining models as a part of our search for a deeper understanding of reality.

5] Methodology

Given this study's theoretical nature, to answer the research question, we developed a constant comparative analysis, a method appropriate for analysing qualitative data. In this approach, the researcher can make conceptual comparisons among distinct contexts, allowing for an account of the phenomenon that transcends the individual settings in which data was originated. According to Glaser and Strauss, in this method, " … the analyst jointly collects, codes, and analyses his data and decides what data to collect next and where to find them in order to develop his theory as it emerges" (Glaser & Strauss, 1967, p. 45). Glaser (1965) points out that the constant comparative method aims to generate and plausibly suggest many properties and hypotheses about a general phenomenon, but considering that it does not search for universal proof, it does not require consideration of *all* available data.

In addition, this approach is suited for this study because it has the potential to link together elements coming from different contexts, which would otherwise remain scattered, thereby fostering trans-situational and cross-contextual relevance (Pawluch, 2005).

For this study, the analytical categories were taken from the theoretical framework, as developed in the previous section: *model objects; theoretical models; general theories; black box; translucent box; abstractions* and *idealizations*. These constructs were then connected to aspects of the historical development of atomic models to help form a coherent explanation of the modelling process, which could, in turn, contribute to enlightening how scientific knowledge relates to reality. This account is presented in the next section.

6] A Model-Based View of Atomic Models

Identified as small indivisible corpuscles in ancient Greek philosophy, atoms started to be related to specific undecomposed chemical elements in Dalton's time, subsequently encouraging further explanations for chemical compounds and reactions. To let more light pass through the "black box" would then mean starting to speculate about what was inside the very atom. This speculation was undertaken by J. J. Thomson in 1904 after he explained the nature of cathode rays, which he imagined as negatively charged subatomic particles, i.e., electrons. Since the electrons would have to be matter components, Thomson pictured the atom as a positively charged uniform sphere with embedded electrons. Albeit simple, this was clearly not a purely black box approach anymore, since it concerned the unobservable internal structure of the atom.

With this idea about the atom, Thomson explained that the scattering of charged particles through matter was caused by a significant number of collisions with a significant number of atoms. A single collision would produce only a minimal deviation, but after many collisions, there would be a cumulative effect. The main new idea contained in Thomson's contribution was a conceptual counterpart of the actual object under study. Therefore, what Thomson initially proposed was a new model object for the atom, meaning a representation of this object that could, a priori, be grafted in general theories to form theoretical models, which, in turn, could be used to foster explanations of many natural phenomena. At least, so expected Thomson. In 1904, he wrote to Ernest Rutherford:

> I have been working hard for some time at the structure of the atom, regarding the atom as built up of a number of corpuscles in equilibrium or steady motion under their mutual repulsions and a central attraction: it is surprising what a lot of interesting results come out.

> I really have hopes of being able to work out a reasonable theory of chemical combination and many other chemical phenomena. (Thomson in Davis & Falconer, 1997, p. 153)

Although Thomson could explain valence, radioactivity, and periodic properties of chemical elements, his hopes were not fulfilled. Subsequent experiments showed that the number of corpuscles in atoms was much smaller than necessary for Thomson's atom to be stable.

Ernest Rutherford and his collaborators subsequently made a new attempt to find out more about atomic structure. Rutherford proposed a series of experiments, conducted by Hans Geiger and Ernest Marsden, in which beams of α and β particles were pointed at a thin piece of gold foil, and the consequent deflections were measured. Data was collected relating the input and output variables, i.e., the beam rectilinear path directions before and after they passed through the atoms of matter. Therefore, instead of assuming the atom could be modelled as Thomson proposed earlier, they initially treated it like a black box again. In so doing, they made it possible not only to test whether Thomson's model was empirically adequate, but also to describe and predict the behaviour of the atom regarding how it scatters α and β particles. In fact, observations made by Geiger and Marsden were incompatible with Thomson's atomic model-object. For example, they found that a small percentage of the α particles experienced a deviation of 90 degrees or more. This would be extremely unlikely to happen in an atom such as the one imagined by Thomson, since the gold foil used as target by Geiger and Marsden was very thin and would not allow for so many collisions to occur.

So, to explain the scattering patterns shown in his black box approach, Rutherford had to draw a new picture of the inner structure of the atom. Possessing an initially superficial, simplistic and opaque model of the atom, which basically just related input and output, Rutherford proceeded to hypothesise the internal structure of this object. To do so, he also used knowledge from electromagnetic theory, such as the relation of electrical forces and potentials. However, that was not enough: he had to invent a different model-object for the atom. In fact, in Rutherford's model-object for the atom, a unobservable new entity was created: the nucleus, a small, dense, positively charged, discrete part of the atom, located at its centre.

In this model, negatively charged particles surrounded the nucleus. Since the nucleus was so small compared to the atom as a whole, Rutherford's atom would be constituted mainly of empty space. Right-angle or more deviations of α particles could then be explained as being caused by a single collision with the atomic nucleus.

In this new model-object known as Rutherford's atom, the effects of electrical fields created by these negative particles were abstracted, as well as the possibility of deviations of α particles due to a single collision with electrons. In addition, the dimensions of α particles and electrons are idealized to be considered concentrated at a point. Therefore, the scattering phenomenon is reduced to an interaction between a rapidly moving particle and the nucleus of the atom being traversed. Other abstractions in Rutherford's analysis include the consideration of the nucleus as being initially at rest and the disregard for possible energy and momentum losses by radiation.

Notwithstanding such departures from the real object, the theoretical model developed by embedding the model-object for the atom invented by Rutherford in previously existing general theories (mainly electromagnetics and dynamics) made it possible to develop a theoretical model which demonstrated good agreement with experimental results. But the crucial challenge to Rutherford's model-object was not an empirical issue, but rather a theoretical one: it was in open contradiction with classical electrodynamics. Rutherford's atom could not be stable because the attractive forces between electrons and the nucleus would drag the former into the latter, hence collapsing the entire atom. Rutherford was aware of this, but explicitly chose to disregard the issue for the time being: "The question of the stability of the atom proposed need not be considered at this stage…" (Rutherford, 1911, p. 3).

While the path from Thomson's to Rutherford's atomic model consisted of a change of model-object, this new challenge would require a change in the general theory. Such a programme was put forward by Niels Bohr shortly thereafter. He identified the problem of atomic stability as due to " … inadequacy of the classical electrodynamics in accounting for the properties of atoms from an atom model as Rutherford's" (Bohr, 1913, p. 3). As did Rutherford, Bohr imagined the atom as a massive nucleus at rest with electrons in circular orbits around it. However, Bohr's proposal relied upon

Planck's theory to state that energy emissions by atoms could not occur in the continuous way implied in classical electrodynamics, but only in quanta. This meant that amounts of energy lost or gained by any particle—including atomic electrons—could exist solely in quantities equal to entire multiples of Planck's constant. As a consequence, just specific electron orbits—meaning specific energies—would be permitted (Bohr, 1913).

By having Planck's theory of radiation as a general theory and Rutherford's atom as a model object, Bohr was then able to derive a new theoretical model predicting the energy levels of atoms containing few electrons. Bohr's theoretical model was quite successful—albeit not perfect—in explaining the atomic spectrum of hydrogen. Spectral hydrogen lines were already known and put in a formula by Johannes Rydberg, but this formula had been developed only empirically, in a black box approach, limited to relating each line's number with the respective wavelengths. The intervening variable—Rydberg's constant—was known empirically, but there was no explanation for its value before Bohr's model, which allowed the calculation of it from known values such as the electron mass and charge and Planck's constant.

Like the previous models, Bohr's atom was teeming with idealizations and abstractions. Initially, the nucleus was assumed to remain at rest; electronic orbits were assumed to be circular and relativistic effects due to the high velocity of moving electrons were omitted. Yet, the resulting theoretical model's success was realised not only for having solved the theoretical problem it originally addressed—i.e., atomic stability—, but also for shedding light on Rydberg's black box for hydrogen spectrum by endowing it with an explanation and situating it inside a contemporary physics framework. Moreover, this theoretical model allowed for the prediction of tBrackett and Pfund series, which had not yet been observed.

Similar to previous atomic models, Bohr's had its limitations. It failed to account for energy levels in atoms with higher atomic numbers and could only predict hydrogen's spectrum in the absence of external electrical and magnetic fields. The latter issue was tackled later by Arnold Sommerfeld, who applied quantum mechanics and relativity as general theories where classical mechanics were applied by Bohr; this resulted both in a new version of Bohr's model-object of the atom (adding elliptical orbits, for instance) and a new theoretical model for the energy of the hydrogen atom, which, in turn, provided an explanation for the fine structure in this atom's spectrum.

This highly summarised account of atomic model development illustrates some of the features of models pointed out by Bunge. First, it shows the possibility of identifying the three basic elements of the modelling process—i.e., model-objects, general theories and theoretical models—, as it exemplifies their dynamics in scientific knowledge construction. Second, it demonstrates how new theoretical models can be created by conjoining the same model object with a different general theory and associating different model objects with the same general theory. In any case, the resulting theoretical model " … is bound to fall short of the complexity of its referent" (Bunge, 1973a, p. 100), since it inherits abstractions, idealizations and approximations present in the other modelling elements to which it relates.

In addition, this brief report shows the relevant roles of black boxes and translucent ones. While Rutherford's atom arose mostly as a model-object invented to help to explain a black box by creating a new unobservable, idealized construct, even more light could be shed throughout the box when Bohr and Sommerfeld enriched it with new general theories. By the same token, the success of theoretical models also helped to pave the way for its related general theories, as was the case for atomic models in relation to quantum mechanics (Eckert, 2014). Finally, the history of atomic models also illustrates how theoretical models constituted the bridges between "pure" theory—contained in general theories—and reality—or, more precisely, our ideas about real objects, i.e., model-objects.

7] Teaching Implications

Throughout the historical development of atomic models, it is possible to witness the construction of several theoretical models for the same object and multiple model-objects for it. The advantage of making explicit the role of some ideas as theoretical models and other ideas as model-objects are: i) to foster the understanding of scientific knowledge as referring immediately to conceptual versions of the real objects, not to real objects themselves; ii) to denote the role of theoretical models as mediators between theory and our ideas about reality; iii) to make explicit how it is both possible and coherent to have multiple theoretical models for the same object, once one understands how these are created; iv) to demonstrate how theoretical models can have different explanatory potentials; and v) to bring up idealizations, abstractions and approximations as creative thought processes, not merely demerits of models. These features consist of possibilities to deal with the teaching issues pointed out at the beginning of this article.

By having Bunge's modelling theory as a framework, the didactic use of the history of science can offer an alternative 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 the preceding section, we illustrated this possibility through the historical case of the development of atomic models, showing how distinct theoretical models to explain atoms' behaviour emerged by inventing new model-objects or adopting different general theories.

This indicates that Bunge's account of scientific models can be helpful when trying to understand several aspects of models, which have been problematic in science education contexts. For example, the notion of a model-object highlights an essential characteristic of scientific knowledge, i.e., that it does not consist of a mirror, a photograph or an exact description of reality: on the contrary, it is a partial representation, idealized and approximate, at best. In addition—what is perhaps the most important thing—this does not constitute a demerit, given that the role of the model object is a productive one, since it has the indispensable role of making our theories testable. Furthermore, when we think about the possible processes of construction of theoretical models in these terms, it is possible to understand why multiple models of the same thing can exist, all of which are legitimate and acceptable within their limitations and contexts. Moreover, the notion of general theory as something different from theoretical models makes the search of science for systematization evident while demonstrating the fecundity of this systematization in producing theoretical models.

Although the transposition of Mario Bunge's ideas to science education made here was exemplified with the use of history of science, the framework developed is also applicable to teaching activities using modelling in the classroom, which does not necessarily have a historical approach. The case of the simple pendulum, for example, can be object of a modelling with an initial black box approach, by empirically obtaining the relations between variables and pendulum regularities (obviously, through the direction of the teacher) and that could be made progressively more translucent through the articulation with the corresponding general theory and the conceptual discussion of the model-object created.

This type of approach could be a way to construct models de novo (Gilbert & Justi, 2016). The model-object and the general theory employed there could be made explicit in other situations to contribute to the formation of new theoretical models that use them. The point to highlight here is the portability of the modelling elements, because it can help develop students' cognitive flexibility, i.e., their recognition and mobilization in other, new situations. This is possible because elements such as model-objects (e.g., point masses) and general theories (e.g., Newton's law) can be articulated in various ways in order to construct a large number of theoretical models—including ones intended for different situations—within a given conceptual domain (such as mechanics).

8] Concluding Remarks

Portides argues that understanding "how scientific theories relate to experiment" is a key meta-scientific component in enhancing the ability to think scientifically (Portides, 2007, p. 700). In this paper, we also claimed that this was a relevant issue for science education contexts, especially in enabling students to assign meaning to scientific concepts and theorisations. In addition, we expanded the question of "how scientific theories relate to experiment" to "how scientific theories relate to reality", since reality is ultimately the reference of scientific knowledge. As we pointed out, students tend to conflate real objects with the knowledge produced about these objects. As with Portides (2007), we also identified the link between reality and scientific knowledge as being performed by models.

To deal with the problem of the relation between scholarly scientific knowledge and reality, it is necessary to have as foundational a framework that allows for understanding this relation, as well as the roles of theory, models, and other elements that take part in the process of modelling. To the extent that the Bungean theory of models offers a consistent and well-articulated framework for these relationships, the transposition of his ideas into the educational context may provide such a basis and potentially contribute to solving this pedagogical problem. Teaching the history of science, along with experimental activities and mathematical skills, can also constitute an alternative method to foster modelling practices in the classroom. In particular, we argued that Bunge's views on models and modelling could offer a potentially fruitful framework to help overcome the separation between scientific theories and reality in science education.

Finally, it must be noted that any proposals whether educational or epistemological, have limitations. In this sense, we want to emphasise that the defence of the framework presented here does not imply the rejection of other possible references. Its development is intended to address specifically the problematic of models exposed at the beginning of this article. As Bunge himself teaches, it is always possible, at least a priori, to approach a problem under different theoretical starting points without this meaning an inconsistency or mutual exclusion. Therefore, adopting other frameworks to address the problem is possible and can complement the contributions we seek to develop here. Besides, the relation between theory and reality focused in this work is not the only role that models play, as already observed by Morgan and Morrison (1999). Thus, other modelling aspects can be discussed and explored, perhaps even more appropriately, by conceptual lenses different from those of Bunge. This means that we understand such lenses as a model of models, among other possible ones.

References

Bohr, N. (1913). On the Constitution of Atoms and Molecules. *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science,* 26(153), 476-502.

Bunge, M. (1973a). *Method, Model and Matter*. Reidel.

Bunge, M. (1973b). *Philosophy of Physics*. Reidel.

Bunge, M. (1977). *Treatise on Basic Philosophy: Ontology I: The Furniture of the World*. Springer.

Bunge, M. (1985). *Treatise on Basic Philosophy: Volume VII: Epistemology and Methodology III: Philosophy of Science and Technology*. Reidel.

Bunge, M. (1991). Una Caricatura de la Ciencia: La Novisima Sociologia de la Ciencia. *Interciencia*, 16(2), 69-77.

Bunge, M. (2001). *Diccionario de Filosofia*. Siglo Veintiuno.

Cartwright, N. (1989). *Nature's Capacities and their Measurement*. Clarendon.

Coll, R. K., France, B. & Taylor, I. (2005). The Role of Models and Analogies in Science Education: Implications from Research. *International Journal of Science Education*, 27(2), 183-198.

Davis, E. A. & Falconer, I. J. (1997). *J. J. Thomson and the Discovery of the Electron*. Taylor & Francis.

Eckert, M. (2014). How Sommerfeld Extended Bohr's Model of the Atom (1913-1916). *The European Physical Journal H*, 39(2), 141-156.

Gebert, H. (1969). Physical Models. *Physics Education*, 4(2), 117-118.

Gilbert, J. K. & Osborne, R. J. (1980). The Use of Models in Science and Science Teaching. *European Journal of Science Education*, 2(1), 3-13.

Gilbert, J. K. & Justi, R. (2016) *Modelling-Based Teaching in Science Education*. Springer.

Gilbert, J.K., Pietrocola, M., Zylbersztajn, A. & Franco, C. (2000). Science and Education: Notions of Reality, Theory and Model. In: Gilbert, J.K., Boulter, C.J. (eds) *Developing Models in Science Education*. Springer.

Glaser, B. G. (1965). The Constant Comparative Method of Qualitative Analysis. *Social Problems*, 12(4), 436–445

Glaser, B.G., & Strauss, A. (1967). *The Discovery of Grounded Theory*. Aldine.

Grosslight, L., Unger, C., Jay, E. & Smith, C. L. (1991). Understanding Models and their Use in Science: Conceptions of Middle and High School Students and Experts. *Journal of Research in Science Teaching*, 28(9), 799-822.

Harrison, A. G. & Treagust, D. F. (2000). A Typology of School Science Models. *International Journal of Science Education*, 22(9), 1011-1026.

Hessen, J. (1997). *Teoría del Conocimiento*. Panamericana.

Hodson, D. (2014). Learning Science, Learning About Science, Doing Science: Different Goals Demand Different Learning Methods. *International Journal of Science Education*, 36(15), 2534-2553.

Justi, R., & Gilbert, J. (2000). History and Philosophy of Science Through Models: Some Challenges in the Case of "The Atom." *International Journal of Science Education*, 22(9), 993–1009.

Krapas, S., Queiroz, G., Colinvaux, D., & Franco, C. (1997). Modelos: uma análise de sentidos na literatura de pesquisa em ensino de Ciências. *Investigações em Ensino de Ciências*, 2(3), 185-205.

Lefkaditou, A., Korfiatis, K., & Hovardas, T. (2014). Contextualising the Teaching and Learning of Ecology: Historical and Philosophical Considerations. In *International Handbook of Research in History, Philosophy and Science Teaching* (pp. 523-550). Springer.

Lombardi, Olimpia, Alberto Cordero, and Ana Rosa Pérez Ransanz, "Philosophy of Science in Latin America", *The Stanford Encyclopedia of Philosophy* (Spring 2020 Edition), Edward N. Zalta (ed.).

Machado, J. & Braga, M. (2016). Can the History of Science Contribute to Modelling in Physics Teaching? The Case of Galilean Studies and Mario Bunge's Epistemology. *Science & Education*, 25(7), 823-836.

Machado, J., & Fernandes, B. L. P. (2021). Model Conceptions in Science Education Research: Features and Trends. *Ciência & Educação*, 27.

Matthews, M. R. (2007). Models in Science and in Science Education: An Introduction. *Science & Education*, 16(7–8), 647–652.

McMullin, E. (1985). Galilean Idealization. *Studies in History and Philosophy of Science Part A*, 16(3), 247-273.

Morgan, M. & Morrison, M. (1999). *Models as Mediators: Perspectives on Natural and Social Science*. Cambridge University Press.

Morrison, M. (2007). Where Have All the Theories Gone? *Philosophy of Science*, 74(20), 195-228.

Niiniluoto, I. (2002). *Critical Scientific Realism*. Oxford University Press.

Palmieri, P. (2003). Mental Models in Galileo's Early Mathematization of Nature. *Studies in History and Philosophy of Science Part A*, *34*(2), 229-264.

Pawluch, D. (2005). Qualitative Analysis : Sociology. In K. Leonard (Ed.), *Encyclopedia of Social Measurement* (pp. 231–236). Elsevier.

Portides, D. (2007). The Relation between Idealisation and Approximation in Scientific Model Construction. *Science & Education*, 16(8), p. 699-724.

Portides, D. (2013). Idealization in Physics Modelling. In *Proceedings of EPSA11 Perspectives and Foundational Problems in Philosophy of Science* (pp. 103-113). Springer.

Quine, W. (1985). *The Time of My Life: An Autobiography*. MIT Press.

Rutherford, E. (1911). The Scattering of Particles by Matter and the Structure of the Atom. *The London, Edinburgh and Dublin Philosophical Magazine and Journal of Science*, 21(125), 669-688.

Schwarz, C. V., Passmore, C., & Reiser, B. J. (2017). *Helping Students Make Sense of the World Using Next Generation Science and Engineering Practices*. NSTA.

Suppe, F. (1989). *The Semantic Conception of Theories and Scientific Realism*. University of Illinois Press.

Taber, K. S. (2012). The Natures of Scientific Thinking: Creativity as the Handmaiden to Logic in the Development of Public and Personal Knowledge. In *Advances in Nature of Science Research* (pp. 51-74). Springer.

Taber, K.S. (2013). The Centrality of Models for Knowledge Claims in Science Education. In: *Modelling Learners and Learning in Science Education*. Springer.

COPYRIGHT AND DISTRIBUTION POLICY