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Models and Modelling in Physics Education: A Critical Re-analysis of Philosophical Underpinnings and Suggestions for Revisions

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Abstract. The model-based view (MBV) of science education, which strives for authenticity in science teaching, is currently seeking support from the philosophical positions related to the Semantic View of Theories (SVT). These recent advances are promising steps towards establishing a robust philosophical framework, but they need revision in so far as they are meant to apply to physics and physics education. It is suggested here that in physics education, attention needs to be guided to the notion of *the empirical reliability of models* and modelling, and to the methodological question of how empirical reliability is established in *the process of making a match between theory and experiment*. The suggested picture – intended for the purposes of physics teacher education – replaces the current more limited philosophical frameworks used in science education with one of a wider scope. Moreover, the revised philosophical background gives a more authentic picture of physics as science, and the modelling activity within it, than the other current stances in the science education.

1. Introduction

Science education, which sets as its goal the elucidation of an authentic picture of science, has drawn much insight from the model-based view (MBV) of science, where models and modelling are seen to take a central role in the justification and formation of knowledge. Educational researchers expect the model-based approach to deeply affect future curricula, instructional methods, and teaching and learning in general (Gobert & Buckley 2000; Justi & Gilbert 2000; Izquierdo-Aymerich & Adúriz-Bravo 2003), as well as teachers' conceptions of the nature of scientific knowledge (Justi & Gilbert 2002; Van Driel & Verloop 2002). The epistemological and methodological questions related to models and modelling directly touch upon philosophical issues concerning the relation of theory to the world as experienced, or as accessed through experiments. Many researchers in science education who advocate the MBV have, consequently, recognised the need to find support for their views from the philosophy of science. The focused and coherent use of a philosophical framework seems to be emerging for purposes of research in learning (Snyder 2000; Adúriz-Bravo & Izquierdo-Aymerich 2005), as well as in teaching and design of didactical approaches (Izquierdo-Aymerich & Adúriz-Bravo 2003; Crawford & Cullin 2004). The philosophy of science underpinning these recent studies goes under different names such as the; 'new view on theories' (Grandy 2003), 'new history and philosophy of science' (Izquierdo-Aymerich & Adúriz-Bravo 2003), or 'cognitive theory of science' (Giere 1988).

These philosophical views currently in use within science education are more or less related to the Semantic View of Theories (SVT) that originates from works by Suppes (1962), Suppe (1977), van Fraassen (1980) and Giere (1988). Within the SVT, the realistic position by Giere (1988, 1999) has been recognised by researchers in science education as a viewpoint which may better connect science and science education together (Izquierdo-Aymerich & Adúriz-Bravo 2003; Crawford & Cullin 2004; Adúriz-Bravo & Izquierdo-Aymerich 2005). One reason for this is that in Giere's philosophy of science, attention is paid to the cognitive and pragmatic factors involved in *doing science*. Another reason is that Giere sees the structure of scientific knowledge through models or clusters of models, and this closely approaches the way mental models and mental representations are used in understanding aspects central for learning. Finally, Giere outlines the relationship between models and reality in the form of realism, embodied by the *notion of similarity* – and the realism is the favoured stance of current views within science education that seek the authentic image of science (Matthews 1994, 1997; Nola 1997; Gilbert et al. 2000).

The SVT and versions of it within philosophical realism are thus promising candidates for a robust background philosophy for science education. However, at least in the case of physics and physics education, Giere's conception of models as well as the SVT itself, both need some revision for the following reasons. First, the SVT is still too limited to acknowledge the required semi-autonomy of models (Morrison 1999; Morrison & Morgan 1999). Second, the SVT does not give an adequate picture of how (at least in physics) the relation between models and the experimentally accessible phenomena to be modelled is bi-directional; these phenomena are not only modelled but also fitted to models (Cartwright 1999). Third, the concept of similarity (Giere 1988) is too vague to clarify how the models are matched with real systems. And fourth, in physics and for physics education, similarity taken in a strictly realistic way as a similarity of representation is questionable, since in physics there is no compelling reason to include this requirement among the attributes of good models; the requirements can be more narrowly based on empirical reliability (Cartwright 1999) or the empirical adequacy of models (van Fraassen 1980).

To make the current philosophical underpinnings of the contemporary science education literature more useful for the purposes of physics education, I propose a revision, which for the most part still fits within the SVT but relaxes some of its restrictions. The decision to concentrate only on physics is motivated by the notion that in physics the role of models and modelling is essential not only epistemologically but also methodologically. The core of physics' methodology is the process where theoretical predictions are connected with the outcome of measurements (Koponen & Mäntylä 2006). Moreover, to give an authentic picture of models and modelling in physics, there is no compelling reason to limit the views only within the philosophical realism.

The intended scope of the revision suggested here is physics teacher education. The choice is motivated by the notion that for teachers it is essential to understand how reality is approached in physics, and what the epistemological as well as methodological issues are. However, understanding these aspects of physics does not necessarily affect how teachers use models and modelling in practical school teaching, but it certainly affects the way they can justify the practical solutions and relate them to physics as science. I will therefore discuss models and modelling from the viewpoint of physics, for using this as a philosophical background in physics teacher education. Recent views on models and modelling in science education are first scrutinised in order to outline their philosophical underpinnings, and to support the argument that a revision of the philosophical basis is needed. Next, I discuss the role of models and modelling in physics as the SVT sees it. Against this background, new suggestions for extending the conceptions already contained in the SVT are discussed, and the question of making a match between theory and experiment, and the role of models and modelling therein, is addressed. It is argued that an authentic image of models and modelling in physics requires a certain bi-directionality; models are developed to match with isolated laboratory phenomena, and these phenomena are fitted to models. Finally, I will suggest that at least in physics education, the requirements of empirical reliability and empirical success are attributes that better correspond to an authentic image of science than those of realism and truth as they are understood in the philosophy of science.

2. The Philosophical Underpinnings of Model-based Views on Science Education

Many researchers advocating a model-based view (MBV) of science education refer to cognitively oriented accounts of science such as the views of Giere (1988, 1999), Giere et al. (2006) and Nersessian (1984, 1995), in which cognitive and process aspects of *doing science* are of importance, and where science is seen through a philosophy that can be called 'naturalised realism'. Usually only very general notions arising from a philosophical background are utilised (see e.g. Clement 2000; Gobert & Buckley 2000; Harrison & Treagust 2000), but some researchers, however, have made their stance more explicit, and have looked for support from the SVT as Giere has outlined it, and from its particular formulation of models (Snyder 2000; Izquierdo-Aymerich & Adúriz-Bravo 2003; Crawford & Cullin 2004). Some researchers and educators (Hestenes 1992; Wells et al. 1995) have drawn support for their approaches from accounts provided by more normative and foundationalist philosophers such as Bunge (1983) and Popper (1935/2002). In addition to these philosophical underpinnings, the views of Kuhn (1996) and Lakatos (1970) appear frequently, but there the interest is in the social and sociological aspect of using models in communicating and expressing knowledge and ideas (see e.g. Gilbert et al. 2000; Justi & Gilbert 2000, 2002; Harrison & Treagust 2000). The role of models in representing ideas and knowledge is certainly a relevant viewpoint in practical teaching and learning,[1] but in what follows I concentrate mostly on the epistemological question of models in representing phenomena of the physical world and the relation of such models to theory. Even in this more limited context, the differences in the philosophical underpinnings are fundamental enough to influence educators' and researchers' conceptions of how knowledge is acquired and justified in physics, what the relation of models to phenomena is, and ultimately, what the authentic image of physics as science is.

2.1. PROVIDING EXPLANATIONS AND PREDICTIONS: OPTING FOR REALISM

The role of models in providing explanations and predictions is perhaps the most common area where epistemological questions are explicitly discussed. This particular role of models is related to the task of representing real systems and their behaviour and, therefore, to questions about the truth-value of models. In these instances, models and modelling are consequently quite often seen from the point of view of realism (Hestenes 1992; Gilbert et al. 2000; Justi & Gilbert 2000, 2002; Nola 2004). However, most authors in science education seem to develop their views on models rather independently from the philosophical underpinnings, and – apart from some very general notions of ontological realism – actually make little use of the deeper notions that are contained in the philosophical views they refer to (for typical examples, see e.g. Harrison & Treagust 2000; Justi & Gilbert 2000, 2002). Still, there are some interesting exceptions where the philosophical framework is detailed and utilised in greater depth.

The approach of Hestenes (1992) regarding models and modelling in physics explicitly underscores the relationship of models to theory and experiment. According to Hestenes, model construction is carried out with comprehensible rules (rules of the game), and then the models are *validated* by matching them with experiments. Hestenes draws insights from Bunge's conception of models, and parallels Bunge (1983) when he emphasises the *mathematical structure of models and their subordination to theory*. The aspects Hestenes stresses in modelling clearly constitute an authentic way of modelling in physics, when known and accepted theory is used as the basis for making predictions. Therefore, in Hestenes' ideas, there is a clear predominance of the verificative justification of knowledge, and the truth-value of models is judged according to the success of such theory-based predictions. This reflects scientific realism, which adopts not only ontological but also epistemological and methodological realism. This stance is quite justified in the limited context in which Hestenes introduces the modelling, but it is doubtful when theory construction or acquisition of knowledge not already captured by existing theory is of interest.

A related approach from theory to models, but somewhat less theory-subordinated, is provided in the work of Crawford and Cullin (2004), where the main epistemological role of models is in explaining and developing understanding of the phenomena of nature. According to them, the scientific process can be depicted as a sequence of making observations, identifying patterns in data, and then developing and testing explanations of these patterns, and as they note, 'such explanations are called scientific models' (Crawford & Cullin 2004). These authors do not explicate their epistemological stance with regard to models, but it is clear that the role of models in providing successful explanations is in focus. This is in agreement with the way they refer to philosophical works by Giere (1988, 1999), Hesse (1963) and Black (1962), where models in explaining and predicting is discussed within the framework realism. The adherence to realism is also evident from their general purpose of 'investigating real-world phenomena; then designing, building, and testing computer models related to the real-world investigation' (Crawford & Cullin 2004, p. 1386). However, Crawford and Cullin do not actually address the question of how these models are produced and how they relate to theory in general, nor have they discussed the question of how the success of models in giving explanations is actually judged. Taking into account the philosophical underpinnings they refer to, something close to Giere's concept of similarity between the models and the real world seems to be involved.

2.2. MODELS AND THEORY: THE SEMANTIC VIEW OF THEORIES

The relation of models to theory, *starting from models to theory*, has been examined in depth only in a few studies. Some exceptions are provided by Snyder (2000) and Izquierdo-Aymerich & Adúriz-Bravo (2003), who approach the problem from a viewpoint where models are seen as the core ingredient of theory, in concordance with the SVT. Snyder (2000) focuses on describing knowledge structures by using hierarchies of models, and bases her account on Giere's conception of models. Snyder examines the use of models in the context of mechanics, and in that, she concentrates on the relationship between quantitative and qualitative representations. Following Giere, Snyder discerns in students' problem-solving a hierarchy of models with various levels of sophistication, and shows that the hierarchical use of models can be well understood form this viewpoint. Snyder's work – although related to problem-solving and classification, and thus not extending towards the area of experiments – is an encouraging example of the uses of a detailed philosophical background for purposes of clarifying the model–theory relationship. Izquierdo-Aymerich & Adúriz-Bravo (2003) have also adopted both the SVT and Giere's model-based view of science in their study of epistemological and cognitive parallels between models and modelling in science and school science. In addition to the relationship of models to theory, they also discuss the relation of models to reality. In answering the latter, they follow Giere in picturing theory as a family of models together with a set of hypotheses that establish the similarity of these models to the real world (Izquierdo-Aymerich & Adúriz-Bravo 2003).

In addition to these broadly scoped views, Nola (2004) has discussed in detail, how Giere's conception of models, and of model to real world relationships, applies to the case of pendulums. Nola's discussion makes a convincing case in favour of models as realistic representations of real systems. To the question 'how we might compare our theories and models with reality' Nola answers in terms of Giere's notion of the degree of 'similarity' and 'fit' of models with real systems. The similarity or fit, on the other hand, is established through comparison of experimental data with model predictions; success achieving agreement is taken as a hallmark of the successful fit of a good degree of similarity (Nola 2004; Giere et al. 2006). Although persuasive at first, this scheme leaves open two important questions: first, whether or not there are resources for assessing the similarity or fit beyond the comparison of experimental data and model predictions, and second, how are models actually constructed and what is the relation of experimental designs and set-ups to the models which are meant to describe them?

2.3. MODELS AS RESEARCH TOOLS: BEYOND THE SEMANTIC VIEW?

An important role of models that is recognised in science education literature is their role as tools for intervention in and manipulation of phenomena (Izquierdo-Aymerich & Adúriz-Bravo 2003; Crawford & Cullin 2004).

For example, Izquierdo-Aymerich and Adúriz-Bravo (2003) discuss the role of scientific activity and scientific research as an attempt to transform nature and interact with it, rather than as an activity for arriving at truths about the world. They note that models (and theory) which fail to reach these goals have little value in science education for students and teachers. Consequently, they follow Hacking (1983) in emphasising that models are used to make sense of the world, with the ultimate objective of an active transformation of nature. They also note that 'facts of the world are heavily reconstructed in the framework of theoretical models' (Izquierdo-Aymerich & Adúriz-Bravo 2003). These viewpoints open up important new aspects concerning the use of models and modelling, and are in good agreement with the physicist's conception of justifying and acquiring knowledge (see e.g. Heidelberger 1998; Riordan 2003; Chang 2004). However, paying full attention to these aspects of transforming, manipulating and intervening in phenomena requires that models be seen as autonomous or semi-autonomous agents, much like research instruments. For this, it should be noted that both the SVT and Giere's model-based view are still too limited and need to be augmented.

In science education, the proponents of the SVT have argued convincingly that it can provide a philosophically robust and sound basis for science education. Recognition of the SVT's value definitely means progress in developing solid and coherent philosophical underpinnings for science education. However, at present only Giere's views have received attention, while other equally important works of relevance to science education have been neglected. For physics education, in particular, one of the most important insights contained in the SVT is the notion how models are capable of making a connection with measurable properties of phenomena. This is a methodological rather than an epistemological problem, and has not yet been adequately discussed in current science (or physics) education literature. More attention needs to be paid to methodological questions related to models in making connections with reality as accessed through experiments, and the question of the semi-autonomy of models with respect to theory and experiment should receive more exact considerations.

3. Models within the Semantic View and the Role of Realism

In the SVT, the task of theory is to present a description of the phenomena within its 'intended scope', so that it is possible to answer questions about the phenomena and their underlying mechanisms (Suppe 1977, pp. 221–230). In the SVT, the phenomena (as isolated physical systems) are addressed in terms of models, and *theory is identified with the set of models* (van Fraassen 1982; Giere 1988, 1999). The best-known positions within the SVT are probably the constructive realism of Giere (1988) and the constructive empiricism of van Fraassen (1980), which give somewhat different answers to the question of how models represent and what their relation to theory is.

In van Fraassen's constructive empiricism, it is enough that theory is *empirically adequate*, and this is the case if the empirically accessible parts of phenomena can be embedded in a 'model of the theory'.

> To present a theory is to specify a family of structures, its *models*; and secondly, to specify certain parts of those models (*the empirical substructures*) as candidates for the direct representation of observable phenomena. (van Fraassen 1980, p. 64)

In fact, with a slight re-interpretation of van Fraassen's way of framing the model to the experiment relationship, one can assume that at least some of the *empirical substructures* come close to what would have been called *experimental law* in 19th century physics.[2] Such empirical substructures (or experimental laws) achieve a great descriptive accuracy in their own limited context, and therefore hold a special position in physics as core ingredients of physics knowledge (van Fraassen 1980; Cartwright 1983, 1999).

In Giere's constructive realism, the relationship between the model and real systems is contained in *similarity relations*, which are expressed by theoretical hypotheses. The model is assumed to represent, in some way, the behaviour and structure of a real system; the structural and process aspects of the model are similar to what it models. Based on this notion, it is argued that theory, in general, can be described as a cluster of models, or, 'as a population of models consisting of related families of models' (Giere 1988, p. 82). In Giere's model-based view, therefore, the question of theory is not central, because there is already 'enough conceptual machinery to say anything about theories that needs saying' (Giere 1988, p. 83). Not only theory but also laws are subsidiary in Giere's conception of science,[3] laws can be regarded as general enough models to provide sufficiently broad basis for all practical purposes (Giere 1988, 1999). It is thus the hierarchical organisation of models which makes it possible to use them in different levels of abstraction and generality and as a basis for general descriptions as needed in different practical situations.

On closer inspection, however, both constructive realism and constructive empiricism say little about the methodological aspects of producing the required empirical adequacy or similarity, which are both methodologically vague notions. For example, in Giere's constructive realism one needs to assume that it is possible to assess the similarity or fit of models with the real world or real systems somehow on a broader basis than just on the basis of experimental data of observable properties of phenomena, and that on the other hand, make inferences of the properties of unobservable entities (see e.g. Giere 1988; Giere et al. 2006). The overall picture seems to be valid as applied to simple enough systems, and e.g. textbook examples of physics, (see e.g. the discussion of the pendulum in Nola 2004). However, in a closer analysis of physics history it turns out that this represents so strong a realist position that many other uses of models fit it uncomfortably. Moreover, such a use of models does not often have a role in forming a physicist's beliefs of the reality of entities. Propositions of unobservable properties of entities or phenomena remain provisional or tentative as long as their 'capabilities' in producing, causing or intervening in some other phenomena is in question. What is essential for a realistic position about entities is the possibility to use the inferred properties of entities in the design of experiments or the design of instruments of investigation – the possibility of intervention (Cartwright 1983; Hacking 1983; Fine 1996; Riordan 2003). This, on the other hand, always involves the use of instruments or devices designed on the basis of the assumed 'capabilities' or 'powers' of the entities (cf. Cartwright 1983). The data such instruments produce are again not direct observations of the reality itself, but instead, measurement data.

Curiously, a similar lack of interest toward the practical and methodological questions of model to experiment relationships is also characteristic of constructive empiricism, which also fails to make definite how the required empirical adequacy is settled. To clarify this important methodological and practical question one needs to turn to other views within the SVT more suitable for describing how models or rather a hierarchy of models are needed to make a match between theoretical representations and experimental data (Suppes 1962; Suppe 1977). However, before examining this question, the relation of the SVT to philosophical realism needs to be discussed.

3.1. THE SEMANTIC VIEW AND PHILOSOPHICAL REALISM

Within the SVT, the term 'semantic' refers to the fact that the model provides a realisation in which the theory is satisfied; the notion of a model is defined in terms of truth. Therefore, questions about reality and the truth of the models (and theories) unavoidably enter the discussions. Realism as a philosophical stance has been seen by many researchers in science education as a natural vantage point, which also guarantees the authentic image of science. As far as ontological realism as a conviction of the existence of mind-independent, autonomous reality with its entities and phenomena is in question, there is no dispute about this. However, realism as a philosophical position is more than a common-sense ontological realism. The demarcation between positions usually called 'realist' and 'anti-realist' is not ontological realism, the dividing line is rather epistemological and methodological realism. Therefore, realistic positions need to be clarified.

Of the varieties of realism, at least ontological, epistemological, methodological and axiological realism must be distinguished, because they address different problems and questions and emphasise different aspects of science. The various realistic positions can be discerned by the following criteria (adapted from Niiniluoto 2002, p. 10):

R1: Reality is ontologically independent from the human mind.
R2a: Claims about the existence of entities have truth-value.
R2b: The concept of truth is applicable to the products of science (concepts, theories and laws).
R3: The best explanation for success of science is that scientific theories are approximately true or sufficiently close to truth.
R4: Truth is an essential aim of science.

Ontological realism adopts positions R1 and R2a and addresses questions concerning the reality of entities, the relations of their properties, and their independence of the observer. R1 combined with R2a is the *minimal realism* or 'common sense realism' of the physicist (cf. Weinberg 1993; Riordan 2003), shared by even those physicists advocating instrumentalist positions with respect to theories of physics (Fuchs & Peres 2000). *Epistemological realism* adopts R2b and asks to what extent is knowledge about the world is possible, while *methodological realism* concentrates on R3 and tries to answer to problem, what is the best method to pursue this knowledge. *Axiological realism* emphasises R4, setting as its goal to assess, whether or not truth is the aim of scientific inquiry. Lastly, *scientific realism* (and critical realism) accepts all conditions R1–R4 (Niiniluoto 2002). In this form, scientific realism contains strong and explicit epistemological (and metaphysical) commitments, and it seems doubtful if many physical scientists are willing to go this far (see e.g. Fine 1996; Heidelberger 1998; Riordan 2003).

The four criteria of realism defined above also clarify the discussion concerning realism in science education. For example, Matthews outlines realism in a way that in most aspects agrees with R1–R4. As he notes, realism so conceived is 'enough to go on with and it is incompatible with empiricism' (Matthews 1994, pp. 177–178). A broader definition of realism associates common-sense realism with notions R1 and R2a only, while taking R2b–R4 as additional assumptions (Nola 1997; Gilbert et al. 2000). There are also even broader formulations of realistic representations and realism, like that by Wartofsky (1979). He takes models to represent in a realistic sense, but enriches the conception of what it means to 'represent', as well as modifies the meaning of 'realism'. The resulting conception of models becomes quite pragmatic, emphasising the practical role of models (or rather, all representations) in achieving only certain representative or descriptive purposes. Indeed, such modifications of realistic, representative accounts of models and modelling seem to be warranted. It is suggested here, that in keeping close enough to physics and avoiding reading in it any additional requirements we actually only need R1 and R2a, while R2b and R3 need to be moderated, to require, instead of truth, *empirical reliability* only.

3.2. EMPIRICAL RELIABILITY WITH MINIMAL REALISM

Physics does not require strong realist interpretations; more important than truth is the *empirical reliability* of knowledge. The empirical reliability of models (or theories) requires only that they produce empirically successful predictions and that the reliability is established in a methodologically accepted way. These are the minimal (and often only generally agreed) criteria for knowledge in physics. Moreover, whether or not the empirical reliability has been fulfilled can be evaluated and assessed, contrary to the claims of 'truth' and 'reality' which are beyond such scrutiny.[4] Therefore, the minimal assumptions we may make to keep close enough to physics without making unwarranted commitments to pre-conceived philosophical positions, are as follows:

r1: Reality and its entities are ontologically independent from observers.
r2: Claims about the existence of entities have truth-value.
r3: Theories of physics are required to be empirically reliable.
r4: The product of physics is empirically reliable knowledge.

The modified (and moderated) theses r1–r4 are no longer entirely compatible with all requirements of strong realism captured by R1–R4, but they do not contradict the realism in minimal form, for which r1–r2 are enough. In particular, empirical reliability now implies empirically successful predictions and is thus a much more moderate condition than R3–R4. However, this is enough to go on in physics. Moreover, r1–r4 are no longer incompatible with some forms of empiricism, although the position outlined by them is not classical empiricism either.[5] Adopting these moderated requirements and assuming that good physics needs only to be empirically reliable, I turn next to the methodological question of how the empirical reliability is acquired and what the role of models in that process is.

4. New Suggestions: Models in Making a Match between Theory and Experiment

The main drawback of the SVT is that it still sees models as subsidiary to theory (Morrison 1999; Morrison & Morgan 1999). As well, most versions of the SVT do not adequately take into account the *methodology of making a match between theory and experiments*. The standard versions of the SVT, moreover, do not see modelling as a bi-directional process, where phenomena (or rather, isolated laboratory phenomena) themselves are fitted to existing models (Cartwright 1999).

4.1. MEDIATING MODELS AS BRIDGES BETWEEN THEORY AND EXPERIMENT

Between the real world of entities and phenomena, and theory, with its concepts, no direct connection or correspondence exists. Neither are the entities of the real world nor its phenomena directly accessible through observation and experimentation. It is only through laboratory experiments and measurable quantities that the regularities contained in phenomena or the entities behind them become accessible, observable (or detectable) and discernible.[6] The measurable properties of phenomena and entities thus provide us with the necessary core of any physical theory. The abstracted and idealised descriptions of these experimental results were once referred to (and still are, in textbooks) as *experimental laws*. It is this kind of experimental law – a kind of 'model of data' – that the theoretical models constructed in physics are meant to be matched with. The form of models we are interested in here mediates between high-level theory and experimental laws, in the above sense.

Several philosophers (Wartofsky 1979; Hughes 1997; Cartwright 1999; Morrison 1999; Morrison & Morgan 1999) have recently discussed the role of models as mediators between theory and experiment. Although these views do not yet constitute a concise theory, they have nevertheless directed attention to several important aspects of models and modelling, overlooked in traditional SVT accounts. In these more recent views, it is reminded that models are very seldom constructed or derived from theory; rather, the models are built using knowledge from many independent sources, sometimes even contradicting the theory (Cartwright 1999; Morrison 1999; Morrison & Morgan 1999). As Morrison remarks:

> ...models themselves are not strictly "theoretical" in the sense of being derived from a coherent theory, some make use of a variety of theoretical and empirical assumptions. (Morrison 1999, p. 45)

The SVT, in maintaining that models provide realisations within which theory is satisfied (as true or empirically adequate), does not allow this kind of freedom. Nevertheless, models carry a substantial amount of well-articulated theoretical knowledge, through the theoretical principles involved in their construction; otherwise, they would not be able to perform their task in mediating between theory and experiment (Morrison 1999; Morrison & Morgan 1999). However, in order to pay attention to the semi-autonomous role of models, it seems to be enough to relax only the models' strict dependence on the theory contained within the SVT. Otherwise the SVT, especially in the form proposed by Suppes (1962) and Suppe (1977) will have insightful aspects to offer for a description of the matchmaking between theory and experiment.

4.2. THE HIERARCHY OF MODELS IN MATCHMAKING

Experimental laws are our bridges to reality, and models mediate between experimental laws and high-level theory. If experimental laws are also taken as models that represent the data in suitable form, the emerging picture begins to resemble Suppes's (1962) view, where a hierarchy of models mediates between theory and measurements. The experimental laws as described above come close to *the empirical substructure* of van Fraassen's constructive empiricism. In addition to the empirical substructure, and following Giere's (1998) suggestion (in slightly modified form), we can allow for *a theoretical superstructure*. It then becomes possible to match the models in the empirical substructure (experimental laws) with theoretical models produced from the theoretical superstructure. This is a process of mutual matching, where both kinds of models are sequentially adjusted and transformed, and where different levels models are involved. An essential feature of this bi-directional process is that models can fulfil their task of connecting experimental results to theory 'only because the model and the measurement had already been structured into a mutually compatible form' (Morrison & Morgan 1999, p. 22).

The process of sequential matchmaking is inherently connected to the use of measuring instruments and the theoretical interpretation of their functioning, an aspect already emphasised by Duhem (1914/1954). Interestingly, the philosophies of Duhem and Suppes both address the question of what is required to establish the empirical adequacy of a theory (and of models as well), and what the role of comparisons between measurements and theory in establishing the empirical adequacy is (for a detailed discussion, see Darling 2002). In both views, the methodological aspects of conducting experiments and manipulating the experimental data are in focus.

For Suppes, the comparison between theory and experiment consists of a sequence of comparisons made between models which are logically of different types. Darling (2002) has elaborated Suppes's view on making a match between theory and experiment by using the scheme of a 'data path' and 'theory path' ultimately converging at a point where comparisons of data and theoretical predictions are possible. On the theory path, one begins by extracting from a physical theory principles or conditions relevant to the class of experiments under question. These data sets (or models of theory) are the theoretical predictions which in the end are compared to the results of the measurements. On the data path, one begins with the actual experimental set-up. The measurement data produced by the experiment cannot be directly compared with the theoretical predictions; to make the comparison it must be transformed, so that it becomes a 'model of the data' (Darling 2002).

For Duhem, the experimental results, the measurement itself and the instrumentation used in the measurements are all of central importance. Consequently, Duhem starts from experiments and introduces a sequence of 'translations' which transform experimental results into a form that ultimately can be annexed to theory.[7] The essence of Duhem's viewpoint is that the theoretical interpretation of the use of instruments, and how they function, is indispensable in every step of the translation sequence; the whole process of interpretation requires a number of theoretical propositions (Darling 2002). In fact, Duhem's position in many ways resembles Suppes's, but Duhem puts more weight on the use of instruments. Nevertheless, both employ a sequence of modelling steps which are needed to narrow the gap between actual measurements and the theoretical predictions; there is a mutual fitting of theoretical models to empirical results, as well as models of empirical results to theoretical models. Moreover, in the latter, not only are results idealised but the experiments themselves are often changed, and the way the phenomena are produced is altered.

4.3. FITTING ISOLATED LABORATORY PHENOMENA TO MODELS

The bi-directional interplay between theory and experiments mediated by models, means – perhaps somewhat unexpectedly – that isolated laboratory *phenomena as well become fitted to models.* In addition to models being altered, the design of experiments which produce the isolated phenomena under study also becomes altered in search of better agreement (Cartwright 1999; Morrison & Morgan 1999). Of course, between isolated laboratory phenomena and natural phenomena there is a fundamental difference; natural phenomena in all their complexity can never be 'fitted to models'. In practice, consequently, much of the experimental activity is focused on adjusting the conditions of experiments so that a better and more reliable fit to models is achieved, *without necessarily altering the model but instead the isolated phenomena itself.*

The repeated adjustments, meaning the transformation of experimental apparatus to better reveal the regularities expected on the basis of researcher's intuition or theoretical preconceptions are sometimes discussed under the notions 'stabilisation of phenomena' or 'creation of phenomena' (Hacking 1983; Buchwald 1994). This viewpoint stresses the idea that the targets of the investigation – and the targets of the modelling – are the *carefully isolated, artificially produced laboratory phenomena*, and not the natural phenomena, which are often too complex to fit into any theoretical pattern as such. Rather, the natural phenomena become analysed and disintegrated into components in terms of the isolated phenomena. Much of the experimental skills are the skills of designing apparatus for making *the suitably isolated phenomena happen, so that they can be understood in terms of models our theories are capable of producing*. As Cartwright notes:

> ...we tailor our systems as much as possible to fit our theories, which is what we do when we want to get the best predictions possible. (Cartwright 1999, p. 9)

She argues further that it is just this aspect of experimentation that makes the theories (and models) successful:

> We build it [the system] to fit the models we know work. Indeed, that is how we manage to get so much into the domain of the laws we know. (Cartwright 1999, p. 28)

If we accept these views – indeed visible in the practice of physics – then the accounts of realism with respect to the truth of theories (and models) are seriously challenged (but not with respect to the reality of entities). It also means a shift in viewpoint, from the use of models as representations of real systems to the use of models as matchmaking tools as well as, also for manipulating and isolating phenomena.[8]

4.4. EMPIRICAL RELIABILITY INSTEAD OF TRUTH

I have emphasised the role of models as tools for connecting the domain of theory with domain of experiment. As far as the methodology of modelling is concerned, it suffices to focus on the empirical reliability of models; i.e., their success in describing and predicting the empirical outcomes of measurements, as well as in designing and engineering physical systems. Epistemologically, however, this is possible only if models have *representative capabilities*. However, 'to represent' now means something other than simply picturing, mirroring or mimicking physical systems, or being 'similar' to a real system. Instead,

> a representation is seen as a kind of rendering – a partial representation that either abstracts from, or translates into another form, the real nature of the system or theory, or one that is capable of embodying only a portion of a system. (Morrison & Morgan 1999, p. 27)

The notion that models 'represent' in a broader sense is also contained in Wartofsky's account of representations, which he takes as 'complex transformations of their objects' (Wartofsky 1979, p. 9). Moreover, many models providing good predictions and which are useful in acquiring empirically reliable knowledge, are only partially faithful to the real systems they are meant to describe (Hughes 1997; Cartwright 1999). As Morrison and Morgan (1999, p. 33) note: 'The model functions as a "representative" rather than a "representation" of a physical system'. When 'to represent' is understood in this broader sense, it becomes apparent that the use of models and modelling does not require one to subscribe to traditional philosophical realism as earlier outlined by theses R1–R4. A better position is obtained by minimal realism, which does not require conditions any stronger than those of r1–r4. This is possible because in the matchmaking between theory and experiment the *empirical reliability* and *empirical success* of models are central, not the truthlikeness (or truth) of representations. This stance has many similarities with constructive empiricism, which assumes that the aims of science are satisfied without literally true stories of how the world is, and instead it holds that the even 'acceptance of a theory may properly involve something less (or other) than belief that it is true' (van Fraassen 1980, p. 9). On the other hand, one may ask if not empirical reliability and empirical success are the very criteria which are used to take something as "true" in science. Taken in this way, there is little difference between moderately realistic positions and the position suggested here.

5. Discussion: Implications for Physics Education

In science education, models are currently considered a means for a more authentic education, facilitating a scientific way to describe, explain and predict the behaviour of the world and acquire knowledge. The philosophical underpinnings for the views put forward in science education often prefer the perspective of the SVT, and within it, scientific realism. I have argued here, that as applied to physics education, this kind of philosophical underpinning, although in many respects promising, still needs to be reconsidered and revised.

First, the appropriate philosophical basis should answer the question of how models connect theory and reality, and it should be realised that this is first and foremost a methodological question. This has not yet been adequately addressed in physics education, although attempts to do so within the SVT are promising. Second, I have proposed that towards this goal and for the purposes of physics education, Suppes's views, where a hierarchy of models mediate between high-level theory and measurement data, need to be considered, and that they could provide a better position than those suggested thus far in science education literature. In the process of making a match, the mediating role of models is bi-directional and it affects and transforms the ways to design and engineer the conditions under which phenomena are studied (or created). Third, and finally, the above notions open up the old question about the role of realism and truth of our representations. I have suggested here that realism as it is understood in philosophical (scientific) realism goes beyond what is required of scientifically sound physics (and thus, of physics education). Instead, minimal realism seems to be enough to go on, and with it, many empiricist views turn out to be as possible as those contained in realism, and they provide a more authentic picture of how models are used in physics.

As a viable solution for a revised philosophical background for physics education, it is suggested here that the following views, inspired by empiricism and embedded within the SVT, should be considered further:

5.1. EMPIRICALLY RELIABLE MODELS ARE OUR BRIDGES TO REALITY

Empirically reliable models make as direct as possible contact to what is detectable and measurable in experiments. The hallmark of empirical reliability is empirical success. Therefore, in order to learn to use models in physics, it is crucial to recognise that this learning needs to be done in the context of experiments and experimentation.

5.2. EMPIRICAL RELIABILITY IS ESTABLISHED IN THE PROCESS OF MATCHMAKING

The empirical reliability of models is established by construction. There is a 3-fold match: first, between experimental data and empirically reliable models (empirical substructures); second, between empirically reliable models and theory (or theoretical models); and third, between empirically reliable models and phenomena themselves. In the latter case, isolated laboratory phenomena are altered to optimally fit the best models. It is possible to justify only the match between empirically reliable models (or empirical substructure) and the results of experiments. In physics teaching, this guides our attention to careful and methodological laboratory work, where students' attention is directed to methodology of measurements.

5.3. AN AUTHENTIC IMAGE OF PHYSICS REQUIRES EMPIRICAL RELIABILITY, BUT ONLY MINIMAL REALISM

Notions 1 and 2 relate to empiricism, and they require only minimal realism as outlined by theses r1–r4. In physics, there are no resources for assessing statements about truth and reality going beyond empirical reliability and empirical success. It is thus a blend of minimal realism and methodological empiricism which may best correspond of an authentic picture of physics.

Some very clear implications arise from these three notions, with respect to teaching physics. First, they shift the viewpoint from the epistemology of modelling to the methodology of modelling. Second, instead of asking questions about the reality and truth of models they shift the emphasis to the reliability, accuracy and usefulness of models. Questions about reality and truth can come naturally after these more methodological questions are assessed. Third, they show that the task of modelling is not only to develop models to explain preconceived phenomena but also that models are tools used to conceive and isolate phenomena. Fourth, they help us to see that experiments and empirical knowledge are an integral part of model construction. The more practical implementations of these ideas in teaching are not discussed here, but suggestions for approaches emphasising the interplay between experiments and theory, compatible with present views, have recently been introduced (Koponen et al. 2004; Koponen & Mäntylä 2006).

Finally, the epistemological views entailed in these notions make considerable use of conceptions usually associated with the anti-realistic positions, but the views involved here do not imply an overarching anti-realism. In order to appropriate this, it should be noted that physics history does not support the argument that physicists are realists beyond ontological or entity realism, and that with respect to theories, many physicists have been anti-realists, even instrumentalists (see discussions in e.g. Fine 1996; Heidelberger 1998; Chang 2004). However, if the realist philosophical underpinnings invoked in the science education literature are meant to be taken seriously, realism should entail more than ontological realism, and such a realistic position is historically unsupported. Instead, physics history opens up many views traditionally discussed within various forms of empiricism. Therefore, I think that the three notions above and their implications on the use of models and modelling should be discussed in physics teacher education, and that educators should pay more attention to these questions. Of course, this does not mean that realistic positions should be rejected; on the contrary, they should be discussed in parallel and as complementary views – but with an understanding that realistic views are more than is required for sound science. Without properly addressing both views, speaking about giving ‘an authentic picture of science’ in the case of physics is not well founded.

6. Conclusions

The model-based view (MBV) of science education strives for authenticity in science teaching, and many of its advocates seek support from philosophical perspectives related to realistic versions of the Semantic View of Theories (SVT). In this paper, I have re-analysed the current philosophical underpinnings of the MBV as they apply to physics and physics education, concluding that the conception of models within the realistic versions of the SVT is too restrictive. Therefore, I suggest an extension of the background philosophical view, to take into account recent notions of models as mediators, models as instruments of investigation and a means of intervention, as well as the bi-directionality of modelling when theory is matched with phenomena (or rather with experimental results).

The background philosophical scheme for the purposes of physics education outlined here suggests that within the MBV of physics and physics education we should focus attention on the following aspects of models and modelling:

1. Empirically reliable models are our bridges to reality.
2. Empirical reliability is established in the process of matchmaking.
3. An authentic image of physics requires empirical reliability, but only minimal realism.

The lessons of empiricism as the methodology of physics are thus adopted here as the basis of the suggested philosophical background, but the ontological and epistemological aspirations of empiricism are rejected. Similarly, common sense ontological realism is accepted, while remaining sceptical of epistemological and metaphysical views entailed in realism (e.g. the possibility to make statements about truth, similarity, or related concepts like verisimilitude, as they are discussed in philosophical realism). The importance of 'empirical reliability' derives from fact that the minimal shared basis of accepted science is found within the realm of establishing empirical reliability, accuracy and empirical success.

Models and modelling as introduced to physics teachers should respond to the three empiricist notions above, which are important but missing components in mainstream physics education literature and physics teacher education. The suggested picture also easily accommodates the practical solutions of existing model-based views of science education, in so far as they have applications in physics education, yet replaces the limited philosophical frameworks so often used to support them with one of a wider scope. Adopting the views proposed here, as well as the pragmatic attitude behind them, may lead us to a renewal of the philosophical underpinnings of physics education, enabling it to give a more authentic picture of physics, and respect the autonomy of physics practices better, than the current philosophical stances adopted in science education. It may, therefore, also lead us to make fundamental changes in what we teach about science and how we teach it for prospective physics teachers.

Notes

[1] The role of models in communicating and representing ideas has been discussed by Gilbert et al. (2000) within the framework of Kuhn's philosophy of science (Kuhn 1996), and by Justi and Gilbert (2000) from the perspective of 'research programs' as suggested by Lakatos (1970). These viewpoints emphasise the historical development, growth and progress of science, as well as the ways in which they relate to science. Lakatos, like Kuhn, stresses the goals and purposes of science, the role of sociology in

agreeing over the goals, as well as questions of how the progress of science can be understood from those vantage points, and thus has little to tell us about the relationship of models to theory and reality; i.e. about the epistemology and methodology of modelling.

[2] Although experimental law is no longer a commonly used expression in physics research literature, the knowledge structure it refers to has not vanished. Results of experiments are still presented in form of well-defined regularities, quite often as mathematical or algebraic formulas. Their status, however, is not one of universal truth but instead of a particular and provisional regularity.

[3] Of the 7249 articles published in the journal *Physical Review E* during 2001–2003, the word 'model' appears in 3013 articles (42%) while only 370 (5%) referred to laws. In *Physical Review B* for the same period there were 14,056 articles, of which 4667 (33%) mentioned models and 251 (2%) laws. The term 'law' (and experimental law) seems to have declined in physics research. The PROLA databases of *Physical Review* show that in the last century there has been indeed a drastic change in occurrences of the words 'model' and 'law' in physics publications. In the period 1898–1939 the relative fraction of words 'model' to 'law' was 0.4, in the 1940s it increased to 1.2 and then steadily to a maximum value of 15.9 in the 1970s (the heyday of models, it seems). After that, the relative fraction has steadily decreased and is now 8.6. This supports Giere's notion that in physics there is no need for laws because models provide all the conceptual machinery needed.

[4] Very seldom are the words 'truth' and 'reality' used in published research reports in physics. Instead, more instrumental expressions like reliability, accuracy, and empirical correctness are abundant. Of course, in casual speech or in writing for a general audience truth and reality are hard currency.

[5] Here I am referring mainly to the philosophy of Mach (1893/1960) and of Duhem (1914/1954), sometimes called phenomenalism. Reading these authors is strongly affected by present-day philosophical views, in particular realism. There seem to be good reasons for re-thinking the anti-realism of Duhem (Needham 1998; Darling 2002) and Mach (Blackmore et al. 2001). In particular, Duhem's way of speaking about 'natural classification' and relating it to the 'ontological order' of real things is actually in disagreement with an anti-realistic interpretation of his philosophy, and as Needham (1998) has pointed out, Duhem's views are not incompatible with realism, although they are opposed to reductionism and naïve realism. Instead of phenomenalist or instrumentalist, Duhem's position is much better understood as that of a pragmatic practicing physicist (Needham 1998; Darling 2002).

[6] The distinction between 'observability' and 'detectability' is actually quite central when differentiating between constructive empiricism and constructive realism. The anti-realism of constructive empiricism as expressed by van Fraassen seems to unravel as soon as its strict adherence to 'observability' is relaxed (Fine 1996). Van Fraassen's views seem to come close to Giere's conception of models, inasmuch as they are not restricted to the condition of 'observability', and when one allows the detectable to replace the observable.

[7] As Darling (2002) has described, Duhem's picture consists of the following sequence of translations: (i) the concrete experimental situation translated into theoretically useful experimental parameters, (ii) the theoretical predictions translated into expected observations (i.e., practically stated predictions), and (iii) the practically stated results translated into symbolic constructions which condense the result of the experiment. In addition, experiments are used to give meaning to the theoretical terms which were used in the translation.

[8] It is instructive to compare this situation with Giere's views of how models are matched with experiments (Giere et al. 2006). In that picture, the similarity or fit of models with real systems is evaluated on basis of agreement between experimental data with model predictions. How this process proceeds, is depicted in flow charts by Giere et al. (2006, pp. 29–33), but in these schemes there is no feedback between construction of models and design of experiments, or process of isolation of phenomena by altering the experimental setup. Also, the methodology of model construction as it parallels with framing the experimental problem which is meant to be its target is not discussed. However, it seems quite possible to alter Giere's description by stressing more the bi-directionality of model construction and design of experiments. Such modification seems to parallel well with the picture discussed here.

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