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# Models as Epistemic Artifacts for Scientific Reasoning in Science Education Research

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**Abstract:** Models are at the core of scientific reasoning and science education. They are especially crucial in scientific and educational contexts where the primary objects of study are unobservables. While empirical science education researchers apply philosophical arguments in their discussions of models and modeling, we in turn look at exemplary empirical studies through the lense of philosophy of science. The studied cases tend to identify modeling with representation, while simultaneously approaching models as tools. We argue that such a dual approach is inconsistent, and suggest considering models as epistemic artifacts instead. The artifactual approach offers many epistemic benefits. The access to unobservable target systems becomes less mysterious when models are not approached as more or less accurate representations, but rather as tools constructed to answer theoretical and empirical questions. Such a question-oriented approach contributes to a more consistent theoretical understanding of modeling and interpretation of the results of empirical research.

**Keywords:** science education; scientific reasoning; models and modeling; philosophy of science



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## 1. Introduction

Imagine a chemistry teacher trying to explain the volume contraction that occurs when water and ethanol are mixed using the famous demonstration of mixing the corresponding volumes of lentils and beans. Since the contraction of the liquid mixture is a non-trivial consequence of a change in hydrogen bonding length and is not mechanistically explainable by smaller molecules that fill the gaps between larger molecules, the lentil-bean demonstration is clearly misleading. Moreover, another major source of confusion is also simultaneously introduced: molecules are identified with solid spheres while imposing the same identification on single atoms. How is a learner supposed to know when it is appropriate to apply such a structural simplification of volume contraction?

One would expect scientists to be prepared to point out the analogies and simplifications used in the bean-lentil model by stating the assumptions involved. Yet, presenting such assumptions is not a trivial task. Not only should the empirical researchers be able to articulate their own theoretical framework, e.g., psychological constructs or observational premises. Moreover, they would simultaneously need to refer to the specific subject on which, e.g., learning groups acquire knowledge or skills. Instead of such explication work, a representational perspective is often adopted, where the notion of representation is, implicitly or explicitly, understood as a structural or other kind of similarity relation between a model and its supposed target system. But how is one able to understand the lentil-bean example according to such a representational notion of modeling? Indeed, the representational approach cannot easily make room for the fact that models are intrinsically tied to human made inferences, actions, and interpretations, and not just to the natural objects, processes, and systems they study.

Apart from chemistry education e.g., [1–4], the representational approach to modeling is also widely present in other fields of science education research e.g., [5–7]. In its reliance on the representational approach to model-based reasoning, science education research

does not differ too much from the mainstream philosophical discussion of modeling (e.g., Weisberg [8]). However, one peculiarity of the science education research literature studied in this article is that the representational conception of modeling features in them side-by-side with the notion of models as tools. By contrast, in philosophical literature, approaching knowledge and human action from the perspective of tool use has traditionally been used to criticize the representational conception of knowledge [9,10]. Another idiosyncrasy of science education research is its tendency to move in between scientific models and students' supposed mental models, as if they were comparable entities. Such an understanding of model-based reasoning has its advantages, for example, in zooming in on the subject matter in question and the students' understanding of it, yet it turns out to be highly problematic in practice.

An unreflective use of the notions of a model and representation, causes problems both in empirical research and in classrooms. If empirical researchers try to discuss their studies within their research communities without properly laying out the assumptions underlying their respective understanding of models, especially when studying scientific reasoning processes, they run the risk of losing common ground, on something that has empirically been observed to be the case [11,12]. Confusions ensue, not because the researchers would have conducted erroneous experiments or miscalculated their statistics, but rather because the results arrived at are not on par with the underlying theoretical assumptions concerning modeling. Likewise, if science teachers are using models merely as representational depictions free from ontological and other assumptions—and not as tools for addressing, e.g., a particular scientific question—it may cause confusion in their learning groups. Such confusions may arise even if every part of the lesson was correct in view of the content to be taught, as well as regarding the level of knowledge of the students.

Given the centrality of the notion of a model in both research and teaching [13–15], we call for a more coherent and explicit treatment of it. With such a theoretical goal in mind, we will argue for the artifactual approach to models [16,17], through presenting and analyzing exemplary empirical and theoretical studies from the field of science education research. The artifactual account approaches models as concretely built artifacts that are constructed by employing various kinds of representational tools. Central for the epistemic functioning of models, according to the artifactual account, is their constrained design that facilitates the study of particular theoretical and empirical questions, and learning from models through their construction and manipulation [18].

In what follows, we study some exemplary studies on modeling within the field of science education research, discussing their degree of internal consistency regarding their respective theoretical frameworks and empirical findings. We then present the artifactual notion of models, and conclude our paper with suggestions on how to think about modeling as a question-oriented activity that employs concrete artifacts for scientific reasoning. Such an artifactual perspective, we claim, can lead to better practice, and stronger mutual understanding within the field.

## 2. Model-Based Reasoning in Empirical Science Education Research

### 2.1. *Scientific Reasoning in General*

Empirical studies in science education research discuss scientific reasoning in various ways. Scientific reasoning is often typically linked to (formal) argumentation and delineated between the theoretical extremes of domain-generality and domain-specificity [19]. Such a middle-ground between the domain-generality and domain-specificity appears well-justified. If, on one hand, scientific reasoning were necessarily tied to specific domains, a general path of doing science would be blocked. On the other hand, too exclusive an attention to domain-generality could lead to general theorizing with (nearly) no contact to domain-specific knowledge. This is often the case with many modeling endeavors that apply cross-disciplinary model templates, such as various network models, to different, often distant domains [20,21].

In addition to the domain-specific dimension of reasoning, the empirical literature has identified general patterns within reasoning processes on the basis of interviewing

researchers about their work, or empirically testing learning environments [22–24]. Such patterns of reasoning are not bound to specific subjects [25–27], but are instead hypothesis-driven, and supposed to work iteratively. They are usually implemented as follows: first, a question is elicited in a research-oriented learning environment and a preliminary hypothesis is formed; second, a suitable scientific investigation is planned and conducted; third, the collected observational or experimental data is processed and referred back to the prior hypothesis; followed finally by the assessment of the hypothesis with respect to the original question, generating new questions and hypotheses, and leading to an iterative process of inquiry.

The aforementioned patterns emerge from different, subject-oriented studies in science education cf. [28–30]. They range from kindergarten [31] and preschools [32,33] to higher education [34]. Given the vast diversity of these implementations, one may ask whether there is a generalizable perspective from which scientific reasoning skills, e.g., formulating adequate questions for respective investigations, could be approached in learning and teaching sciences. One such perspective is provided by model-based reasoning.

### *2.2. Model-Based Scientific Reasoning*

Models are an active area of research within science education research. A host of different perspectives on models and modeling have been introduced and further developed, starting from a focus on visualization [35], to presenting a broad, comprehensive overview of different perspectives on modeling [14].

A substantial part of the discussion of models and modeling in the literature on scientific reasoning aims at straddling the divide between general modeling methods and subject-specific applications. In this regard, models have often been considered as mental or abstract entities, that express formal relations between propositions [36,37], as heuristic devices serving to generate concrete analogies [38], or connecting disciplinary knowledge to data, thus generating explanations [39]. When turning to the generalization-oriented end of the field, assessments of competencies with regard to model-based reasoning [12,40,41] focus on the reasoning processes of learners. As such, the role of models as tools for reasoning within research processes is understood as competency-based cf. [42], and it is presently under vast empirical investigation, since it relates closely to international educational standards, thus shaping the teaching and learning of science.

Within science education research, the notion of “model-being” has offered a prominent approach to the ontology of models [43]. This approach draws together a collection of different perspectives, incorporating also considerations from the philosophy of science, and providing the foundation for the competence model of model competence [44,45]. The related epistemological notion of models is agent-based [46,47]. The agent-based perspective addresses the circumstances in which a model is referred to as such: who, where, when, and to what end does a human judge an object as being a model [48,49]? Despite several empirical educational studies e.g., [50–52], the understanding of models in science [53] and science education [11] remains diverse. Such diversity in understanding has led to an astonishing [44] as well as surprising [43] diversity in model classification schemes. It is, therefore, crucial to further examine the concepts, terminologies, and differentiations native to science education in order to pave the way for a more unified analysis of models and model-based reasoning in science education research [54].

### *2.3. Examples from Science Education Research*

In this section, we will discuss the incoherent treatment of models in science education research, using empirical examples. We begin by presenting two detailed cases, followed by shorter analyses as well as a discussion of a well-received theoretical approach to models. On the basis of our observations on these studies, we call for a more consistent use of the artifactual notion of models. The studies chosen are exemplary in that they are careful in articulating how they understand the notion of a model, and modeling as a particular kind of theoretical reasoning. However, their conclusions seem partially inconsistent in that their

theoretical starting points do not necessarily align with their empirical findings, a problem that we trace back to the authors' representational stance towards models and modeling.

### 2.3.1. Models as Generative Tools

Schwarz et al. [5] provide an interesting case of a partially inconsistent treatment of models in that they argue for understanding models as generative tools at the level of their empirical analysis, yet defining models in a more traditional representational and abstract way. The authors report a learning progression among primary and middle school students where the more sophisticated way of using and understanding models is to view them as tools that "[...] can support [the students'] thinking about existing and new phenomena." (p. 640), instead of understanding models as literal illustrations of what a single phenomenon is like. At the higher end of this progression, students are able to construct multiple models of related phenomena and appreciate their respective advantages and weaknesses.

Similarly, Schwarz et al. elaborate on students' metamodeling [27,55,56] knowledge: the ability of the learner to elucidate inconsistencies which, in turn, can help her and her teacher productively intervene in learning processes, e.g., by turning the inconsistencies into starting points for conceptual change [57]. Such metamodeling knowledge concerns the learner's understanding of models and modeling in science, and progresses from considering models as "[...] good or bad replicas of the phenomenon [...]" (p. 647) to that of viewing them as explanatory and changeable tools, whose changes are crucial for developing new questions. The same goes for the elements of scientific practice, i.e., what learners actually do within the boundaries of their tasks [41,58,59].

In spite of their practice-oriented approach to models as tools, Schwarz et al. define a model as "[...] an abstract, simplified, representation of a system of phenomena that makes its central feature explicit and visible and can be used to generate explanations and predictions." (ibid. p. 633). Moreover, the authors distinguish models from other representations:

"It is important to clarify that not all representations are models. Models are specialized representations that embody aspects of mechanism, causality, or function to illustrate, explain, and predict phenomena." (ibid. p. 634).

In referring to the function of models, the authors ascribe to the agent-based account of models (to be discussed more in detail in the sections below). Consequently, it is the users' judgment about the proper means to serve a particular purpose that is crucial for something to function as a model. Yet, at the same time, the authors still hold on to the realist [60] understanding of models as objective representations of systems/phenomena. Moreover, Schwarz et al. assess the students' success in terms of what they think about the respective phenomena, leading to the question of whether the modeling activity would not be considered successful if a phenomenon were not recovered correctly. But the correctness of the students' supposed mental content would be hard to assess if, say, the targeted system in question were on a submicroscopic level. Or, alternatively, would the modeling activity be successful if a learner "[...] consider[ed] how the world could behave according to various models" (ibid. p. 640)?

The definition of models proposed by Schwarz et al. tries to bridge the gap between models as representations and models as tools, while in their empirical study the students' progression clearly proceeds from naive realist correspondence between a model and a phenomenon towards more reflective uses of models as tools for scientific reasoning. Moreover, their notion of models as abstract representations of phenomena does not seem to suit the concrete examples of the models produced by the students in the empirical study. It is these concrete models rendered by different representational means – pictures, symbols, and language – that researchers focus on (in addition to students' commentary) and not any abstract mental models within students' heads.

On the one hand, Schwarz et al. consider representing, or rather depicting, phenomena, and iteratively revising for better or alternative explanations and predictions as a central

defining aspect of a successful modeling cycle (“elements of practice”). On the other hand, the authors also refer to models as means of eliciting What If? questions (“metaknowledge”). These aspects are not mutually exclusive. However, without explicating the connection between realistically conceived representational aspects of models, and the progression towards a more instrumentalist understanding of them, the epistemological stance of the authors remains unclear. Finally, the authors treat both visible (e.g., a shadow emerges), as well as non-perceivable (e.g., particle movement) target systems, as representable on the same scale. It appears to us that these problems concerning the interpretation of their empirical study are due, at least in part, to the unexplained, and to some extent inconsistent, notion of models with which the authors operate. While we have thus detected inconsistencies between the different parts of the study of Schwarz et al., we wish to emphasize that we do not contest their empirical study or the learning activity reported, but rather the concessions that their instrumental view on modeling nevertheless makes to representational realism.

### 2.3.2. Model-Based Reasoning and NOSI Views

As a second example, we analyze a study from chemistry education research [61] that attempts to link a three-dimensional framework of scientific reasoning competencies (i.e., observing as theory-driven activity, experimenting as manipulation of variables, and using models as tools for inquiry) with views on the nature of scientific inquiry (the so-called NOSI views). Models are important for testing “[...] hypotheses about an original object [...]” (ibid. p. 2720). The reference to original objects is crucial for the authors’ definition of models:

“The model serves as [a] substitute object [...] for an original object when these objects are not available—due to ethical or practical reasons, for example. Students use the model not only to derive a hypothesis or to explain a phenomenon but also to derive data about the original object with regard to their research questions. They test models against data on the underlying original object and reflect the validity of their assumptions.” (ibid. p. 2719)

We would like to highlight that Reith and Nehring simultaneously present models both as tools, i.e., human-shaped constructs, and as surrogates for non-perceivables, i.e., structural representations. Similarly to Schwarz et al., this conflation results in an inconsistent view on models. Reith and Nehring claim that a “naive view” on models considers a model “as an exact copy of reality” (ibid. 2720). Such a view supposes that a surrogate could directly represent atomic features, e.g., by using lentils and beans. An “informed view”, in contrast, “[...] [carries] out investigations on models. [Scientists] test hypotheses about an original object using models” (ibid. p. 2720). However, the authors do not explicitly delineate the circumstances under which a model object is a mere copy of reality (i.e., a direct representation), or when to refer to it as an appropriate tool to represent assumptions about a target system. Moreover, we wish to point out that introducing models as surrogates for original objects, such as assumed submicroscopic entities, runs the risk of reifying these entities in principle, thus falling back on a naive view time and again. Such a view would make the example of mixing legumes as a representation of the respective submicroscopic system to learn something about volume contraction irrelevant at best. The vegetables can hardly represent smaller/larger molecules with regard to canonical mechanistic explanations, i.e., changes in hydrogen bond length. The artifactual notion of models does not start from assuming such a possibility of direct representation, thus lifting the argumentative burden when it comes to the supposed structure of non-perceivables. However, if a teacher would like to introduce how scientific modeling works, surrogate reasoning on the basis of the simplified legumes-molecules correspondence does not add value to the learning environment unless this correspondence is further elaborated. In such a case, understanding the hypothetical nature of the model would be the very point of the exercise. If the same teacher would like to convey canonical knowledge about how molecules are supposedly structured, then the lentil-bean demonstration is inappropriate,



given the numerous and partly contradictory portrayals of submicroscopic entities in, e.g., chemistry textbooks. With this in mind, it would be helpful if science education researchers, exemplified by Reith and Nehring as well as our other cases, refrained from constituting their understanding of modeling via a dyadic relation between models and target systems. We will elaborate the artifactual alternative in the respective sections.

### 2.3.3. Further Studies on Modeling

The works of Schwarz et al. and Reith and Nehring provide examples of the many cases within the field of science education research where, in our view, more consistency in how models are approached and defined would have strengthened their educational implications. In this section, we give a brief overview of some other studies, representative of the current state-of-the-art in the field of science education. What they have in common is that they tend to take a largely unarticulated representational stance towards models, while simultaneously treating models as tools. A more reflective and differentiated approach that pays heed to different kinds of representational tools and their epistemic affordances would have been more appropriate. Such an approach would help addressing, e.g., the difficulties science learners face in acquiring generalizable knowledge when they are confronted with symbolic abstract representations that are presented as mere surrogates for unobservables (e.g., particles, forces or pedigrees) [62,63].

Cheng et al. [6] present models as epistemic tools “[...] to represent [students’ and teachers’] ideas, or to coherently explain the mechanisms underlying target events.” (2019, p. 5). The notion of a model as an abstract representation seems to provide purchase both to students’ and teachers’ ideas and to the real-world target systems. Abstraction plays a crucial role in both cases, as it allows treating the subjects’ ideas as mental models, as well as scientific models as abstract theoretical representations of mechanisms underlying the phenomena. However, a mental model of a theoretical idea and the allegedly correct representation of a submicroscopic target event are two different things. Additionally, if models are considered as abstract representations, why would a student be assessed as a more advanced modeler if she were able to visualize submicroscopic mechanisms, i.e., sketching what is considered a structurally correct depiction of magnetic field lines? In our view, this would testify to the students’ ability to employ cultural representational tools correctly, which is not accounted for when models are conceived of as abstractions.

Luca and Zacharia [64] neither clearly distinguish the students’ supposed mental models from models of external real-world target systems, nor pay due attention to the importance of the external representational tools with which models are constructed. They point out that “[...] models can be both concrete and conceptual (i.e., models we create in our mind) in nature, in our case we refer to external/physical models.” (p. 195). Yet in their discussion of model construction, students are supposed to “[...] mentally bring the model’s content/elements together in order for the model to take shape (have a structure). This cognitive process takes place immediately before learners start constructing their concrete artifacts/models.” (ibid.). Consequently, models reduce to the “[...] externalization of the components and underlying mechanism of a phenomenon/system”. How did the students have access to the underlying mechanics of a phenomenon/system in the first place? Only by collecting observations and experiences, as Louca and Zacharia seem to suggest? This question becomes all the more puzzling as the authors judge the accuracy of a model in terms of how well it represents the features of a respective phenomenon. The study focuses on phenomena at the macroscopic level, yet purports to apply to the representation of the underlying (unobservable) mechanisms as well.

Likewise, when turning to chemistry-focused studies, the question of how a learner could gain competency in handling the problem of unobservable structures remains challenging. Stieff et al. [7] work on what they label as concrete molecular models, i.e., three-dimensional ball-and-stick objects for grasping spatial structures of submicroscopic targets. The authors stress the importance of the empirical investigation of representational competence, which they measure by a test of translating between different chemical depictions of molecules, e.g., translating from the Newman projection to the Fischer projection.

However, such an approach already presupposes a structurally adequate relation between the projections and their respective target systems and thus, elucidates how the participants are able to express and communicate certified knowledge about the atomic scale (ibid., p. 345).

Oliva et al. [65] studied the competence of modeling among secondary students learning about chemical change. Various kinds of representational tools were used (fruits and bowls, Lego pieces, balls of plasticine, discs of colored cards, etc.) “[...] as mediators between the students’ intuitive understanding and school science models.” (p. 751). The authors used several different qualitative and quantitative methods of data analysis. They delineated modeling as an activity employing a range of inferential and reasoning processes that require the students to be able to “[...] interpret, handle, and express phenomena and situations using as certain variety of signs, whether propositional or iconic in format [...]” (p. 753). In their analysis, Oliva et al. tend to conflate mental models and scientific models, in that they relate the students supposed “intuitive models” to “school science models” implying that the application of the same notion of a model to both enables their comparison. Moreover, despite their attention to actual representational tools, they invoke a meta-representational perspective to draw together and evaluate multiple representations. Yet, they do not explicitly attempt to state the conditions under which such an evaluation would be judged to be adequate or successful. Provided that Oliva et al. also subscribe to the models-as-tools approach, it would have been advantageous to address the contributions of different kinds of representational tools in producing scientific understanding as well, rather than focusing only on their supposed unification at the meta-representational level.

#### 2.3.4. *Models of* and *Models for*

The theoretical discussion of models within science education research attempts to navigate between models as tools and models as representations, but not always entirely consistently. Gouvea and Passmore [47] make a distinction between *models of* and *models for*, following Fox-Keller [66], who views models in molecular biology as tools for both theoretical reflection and instruments for material intervention. Gouvea and Passmore argue that “[...] the models of account [of models] often comes alongside models for, which makes it seem like an alternative on equal footing” (ibid. p. 57). They are critical of such attempts, advocating for approaching scientific models as tools for understanding, explanation, and prediction, especially in classroom settings. In their view, the *models of* accounts “[...] are less able to support students’ epistemic agency in doing science because they tend to treat models as representations of what is known rather than as tools to be used in generating new knowledge.” (ibid, p. 50).

Although Gouvea and Passmore are focusing on science classrooms, they also put forth a more general agent-based conception, inspired by the pragmatic accounts of scientific representation within philosophy of science. While we find their agent-based conception of modeling interesting, and also deserving of philosophical attention, some clarification of what they mean by representation would be needed. However, despite their stated intention of approaching models primarily as tools, “i.e., models for a purpose”, their model appears to take the “representational axis” of *models of* on par with the “epistemic axis” of *models for* cf. [46]. As a consequence, the authors distinguish the representational relationship between a model and “a phenomenon”, from the understanding of seeking questions and other epistemic aims of the model. To be sure, Gouvea and Passmore underline that the “[...] two axes are interdependent and inform and constrain each other.” (ibid. p. 53). The epistemic agents, in their view, “[...] specify how models will represent phenomena [...]” (ibid.), while the representational axis concerns the “[...] respects and degrees the model represents the features of some phenomenon.” (ibid.). Yet, given that they do not explicate the notion of representation, it is difficult to tell what they in fact are committed to concerning the representational axis of their account. Gouvea and Passmore claim that their agent-based conception of a model is based on the work of Suárez [67,68] and Giere [46], but these pragmatic accounts would not separate the representational axis from the epistemic axis. Instead, the epistemic aims of the model users are an integral

part of Suárez's and Giere's analyses of representation (i.e., the "representational axis" of Gouvea and Passmore).

In order to see what is at stake more clearly, in the next sections we will provide a brief overview of the philosophical discussion of models and representation. This overview is followed by our suggestion as to how the artifactual account of models as tools should be framed, such that it does not get subsumed by the representational account. Two things are especially important in this regard. First, although models are constructed by using representational tools, the systems specified by these tools do not need to accurately represent any real-world target system. They can also compose fictional, or merely hypothetical systems, addressing various possibilities and impossibilities [69]. Second, the crucial challenge for any account that seeks to approach models as tools is to explain how they could provide scientific understanding without falling back on the representationalist assumption that they do so in virtue of representing some real-world target system more or less accurately.

The artifactual account seeks to account for these challenges by focusing on the scientific and empirical questions models are constructed to answer, instead of supposing that models would need to have any determinable and fixed relationship to some real-world target system. From this perspective, *models of* are *models for*.

### 3. Contemporary Philosophical Perspectives on Models

As we have discussed above, there appears to be a tension in the science education literature about whether to consider models as tools or representations. The studies discussed above treat models as tools while simultaneously adhering to an unexplained notion of representation. This bifold strategy tends to lead to incompatibilities at both the theoretical and empirical levels. That is precisely what the artifactual account of modeling aims to avoid.

We have found that while the notion of models as epistemic tools has gained traction in science education research [55,70], the notion has also been used inconsistently. However, the problems involved do not certainly concern just science education researchers. They are present also in those contemporary philosophical accounts of models and representation that approach the epistemic value of modeling in terms of representation, yet also invoke pragmatic aspects, i.e., factors relating to the use of models (e.g., [71,72]).

For example, Chakravartty [72] distinguishes between the informational and functional dimensions of modeling. The functional dimension of models refers to their capacities to support scientific reasoning, while the informational dimension relies on representation, conceived loosely as some kind of similarity between a model and its target system. Accordingly, the functional dimension presumes the informational dimension. Chakravartty asks: "how [...] could such [inferential and reasoning] practices be facilitated successfully, were it not for some sort of similarity between the representation and the thing it represents—is it a miracle?" (ibid. 201). We suspect that the same kind of reasoning motivates the attempt of science education researchers to merge the notion of models as tools with the idea of representation: if the world behaves as if it were made of invisible particles, why not accept the inference to the best explanation (and the world it depicts)?

The question posed by Chakravartty is thorny indeed as we will discuss in the next sections, and yet, it quite obviously tends to put the cart before the horse. At least when it comes to scientific practice, models are frequently tools for probing what kinds of systems and causal processes might bring about particular kinds of phenomena. Consequently, they are tools for finding out what might be the case instead of representing what is known to be the case (though successful models may gain the status of certified knowledge over time).

#### 3.1. Perspectives on Representation

The idea that modeling has something to do with representation has a long history within philosophy of science, yet Suárez [73] finds out that "the modeling attitude" of both the British (e.g., Thomson and Maxwell) and German scientists and philosophers (e.g., Helmholtz, Hertz, and Boltzmann) of the 19th century, were in fact nuanced. Apart from relying on similarity, resemblance, and analogy, the scientists in question were acutely



aware, according to Suárez, about the relativity of knowledge. Boltzmann's Encyclopedia Britannica entry, "Models", is especially interesting in this regard [74]. On one hand, he writes about models as "representations in thought" and on the other, he invokes the material and tangible objects that scientists have created for assisting their thoughts.

This practice-oriented tradition of considering models as concrete things or their mental images later on became entangled with the semantic and syntactic conceptions of theories with their notion of a model derived from mathematical logic. The resulting "model muddle" [75], does not, however, mean that the notion of a model itself would be vague cf. [47]. Rather, the word model is used in various ways, in different contexts. As our focus is on science education, we limit ourselves to those philosophical discussions that explicitly concern models in scientific practice. Two contemporary discussions are of special interest in this regard: the pragmatic accounts of representation, and the accounts of modeling that instead of concentrating on the representational relationship, address model construction. The latter accounts study how scientists learn from building and manipulating hypothetical systems, frequently called models, without supposing that such model systems would accurately reproduce some features of some target systems of interest.

### 3.1.1. The Pragmatic Account of Representation

The pragmatic accounts of representation aim to provide an alternative to the so-called substantive accounts of representation. Such substantive accounts—i.e., structural or other less formal similarity accounts—seek to explain how models give us knowledge by asking how a model represents its target system. The answer is provided by the relationship between the constituent parts and relations of the model and those of its supposed target system. In other words, such accounts analyze representation in terms of a structural, or some other kind of similarity relation, between the model and its target. Yet, the structuralist and similarity accounts of representation have been rather conclusively criticized within the recent philosophy of science discussion: they have been found lacking when it comes to both their logical and practical dimensions [76,77]. As a result, several structuralist philosophers have attempted to amend their accounts of representation by either accommodating some specific criticisms concerning e.g., the direction of representation [78], or by extending their account of representation by including pragmatic elements with it [79]. On the other hand, many philosophers have increasingly embraced a pragmatic approach to models and representation.

To put it bluntly, the basic issue is this: the pragmatists of scientific representation claim that it is not possible to analyze the representational relationship without making the users and their aims an integral part of it. In terms of Gouveau and Passmore's agent-based conception of models, this would mean that the representational and epistemic axes would coalesce instead of the remaining separate dimensions of modeling. For example, Giere [80] analyzes scientific representation as a four-place relationship: "S uses M to represent W for purposes P", where S is an individual scientist, group of them or a scientific community, M is a model, and W stands for an "aspect of the real world, a (kind of) thing or event." This form can be translated into the following, more informal statement: "Scientists use models to represent aspects of the world for various purposes" (ibid. p. 747). In other words, the users' goals become a part of the definition of representation and as a result, one cannot analyze representation without taking them into account. Suárez [67,68] also grounds his account of representation in the representing activity of modelers. His inferential account of representation has two parts: the *representational force* and the *inferential capacities*.

The representational force of a model is due to the practice of scientists using it as a representation of an intended target. Yet, representational force alone is not enough to make any model a scientific representation. Consequently, in order to function as a scientific representation, the model must possess inferential capacities enabling a competent user to draw valid inferences regarding the target.

What is important, then, to note about the aforementioned pragmatic accounts of representation is their minimal nature: a model represents a target system if it is used to

represent. That in turn, according to Suárez, is based on the inferential capacities of the model, and some norms concerning valid inferences. What those inferential capacities and norms consist of, Suárez does not say. As a result, pragmatists do not say anything substantive about representation, as they do not invoke any deeper constituent relation, such as similarity or structural mapping, between the parts of the model and the parts of the target. What pragmatists are in fact saying is that a model is a representation, if it is used as such. And such a notion of representation does not, by design, explain why models give us knowledge, something that the substantive accounts attempted to do.

The question then becomes: How can one understand how models give us knowledge if representation is trimmed down into such a thin notion that it cannot explain the epistemic productivity of modeling? The answer would need to be sought for somewhere other than from the notion of representation.

### 3.1.2. Model Construction

Morrison and Morgan [81] focus on learning from constructing models instead of using them as representations. They approach models as investigative instruments, whose construction and manipulation enable scientists to learn from them. They view models, rather than as representations, as mediators between theory and data. Likewise, Weisberg [8] considers models as independent from any uniquely determinable relationships to the worldly target systems (ibid. p. 218). Modeling is for Weisberg an art of *indirect representation*, one of building and studying hypothetical systems that will only be related to some particular real-world systems at a later stage of the modeling cycle, if at all.

Many areas of contemporary modeling testify to such an indirect approach with only a few manifest ties to some clearly identifiable target systems. For example, economics has often been accused of modeling without an attempt to relate the highly abstract models to economic realities [82]. The same kinds of concerns have also been raised in biology [83].

Despite paving a way for understanding models as tools, both Morrison and Morgan, as well as Weisberg, eventually invoke the notion of representation as well. Morrison and Morgan are careful to note, however, that they do not consider representation to be “mirroring” or “correspondence”, yet they do not develop their notion of representation any further. They mainly note that it should be thought of as “[...] a kind of rendering—a partial representation that either abstracts from, or translates into another form, the real nature of the system or a theory, or one that is capable of embodying only a portion of a system. [81], p. 27.” Weisberg [84] formulates a formal account of similarity on the basis of Tversky’s set-theoretic account [85] that has not succeeded to create any noticeable interest in the philosophy of science community.

To sum up, the lively philosophical discussion of modeling and representation has not settled on any one notion of representation. The structuralist and similarity accounts of representation have proven difficult to flesh out in any satisfactory fashion, while the pragmatist accounts have remained overly deflationary. Given these difficulties concerning the notion of representation, the artifactual approach to models builds directly on the idea that models are human-made objects, whose construction and use in scientific practices is the key to their epistemic value.

## 4. Models as Epistemic Artifacts

Instead of assuming that models more or less faithfully represent real-world target systems, the artifactual account focuses on how models as purposefully designed artifacts provide access to the empirical and theoretical questions scientists are interested in. According to a standard philosophical definition, artifacts are intentionally made or altered objects, whose aim is to accomplish some purpose [86]. Such definition pays heed to (i) the *aim* that an object has in some human practice and (ii) its *intentional production or alteration* that involves the use and modification of various kinds of materials. Consequently, from the artifactual perspective scientific models are human-made objects that are typically designed for answering some pending scientific problems and built by making use of a variety of representational tools (i.e., various symbolic, semiotic, and material resources).

Both of these aspects of model construction—purposeful design and the representational tools employed—are important for how a model can provide access to a problem scientists are dealing with.

#### 4.1. Purposeful Design

The artifactual account envisages models as human-made objects that can have multiple epistemic uses. In science and science education, they can be used for explanatory, predictive, and assessment purposes, for example. Traditionally, especially the explanatory and understanding bearing dimensions of modeling have been accounted for by appealing to representation. Instead of approaching models as representations of real-world target systems, the artifactual account seeks to analyze the epistemic dimension of models through their interrogative function: addressing the scientific questions models are designed to answer. The constrained construction of a model is the key to its interrogative functioning. Models typically consist of a system of dependencies, designed to answer a pending scientific question, motivated by theoretical and/or empirical considerations [18,47,87]. In other words, relevant theoretical and empirical knowledge needs to be built into it, both through its specific construction and the question(s) it addresses.

For example, in constructing his version of the Lotka-Volterra model, Volterra set out to answer the question of whether the variations in the populations of predators and prey could be produced solely by “[...] the purely internal phenomenon, due only to the reproductive power and to the voracity of the species as if they were alone. [88], p. 5.” To study this question, Volterra wrote a pair of nonlinear differential equations concentrating only on the dynamics between two species, one of which preys on the other, while also acknowledging the importance of external causes for the actual fluctuations in populations. Indeed, at the time when he published his results, the fluctuations in predator and prey populations were usually attributed to some external causes [89]. Akerlof’s celebrated model of the “market for lemons” that earned him a Nobel prize provides an example from economics. It studies through a simplified model of used cars the question of how quality uncertainty can lead the bad quality cars to drive out the better quality cars, leading even to market collapse.

What is important to note about both Volterra’s and Akerlof’s models is that they are not inherently tied to any specific target system, but are rather hypothetical systems constructed to study general theoretical questions. The general character of the dynamics they study have allowed for their application to sundry other problems.

Alfred Lotka used the Lotka-Volterra model to study, apart from biological systems, also chemical systems. Later on, the Lotka-Volterra equations were applied across different disciplines to study various kinds of target-systems, ranging from class struggle to models of technology diffusion [20]. Moreover, the Lotka-Volterra equations have been used as a basic simple model to study the complex behavior of nonlinear systems [90]. Akerlof, in turn, did not intend in his classic article to only study markets for used cars. In fact, the market for used cars was for him simply a “finger exercise” chosen for its “[...] concreteness and ease in understanding rather than for its importance or realism” (p. 489). Akerlof’s focus was on the effects of asymmetric information more generally, and in his famous article he proceeds from presenting the model of used cars to study its implications for various, more important topics, such as the health insurance market, the employment of minorities, and credit markets in underdeveloped countries.

The artifactual perspective can better capture the *initial motivation underlying the construction* of such exemplary models as the Lotka-Volterra model and Akerlof model. From the perspective of scientific practice, to which science education naturally relates on a large scale, one of the main problems of the representational approach is due to its basic unit of analysis: the model-target pair.

Viewing models as inherently targeting a particular real-world system leads to problems concerning their accuracy and misrepresentation, but more importantly, misses their most important scientific contributions. Consequently, the artifactual approach focuses on the questions models are designed to address. Due to their interrogative function, models

are already embedded in existing theoretical and empirical knowledge, e.g., knowledge concerning fluctuations in populations, or market failures due to degrading quality of goods offered. Instead of gesturing at (an unexplained notion of) representation, the artifactual account zooms in on model construction and the access it bestows for further scientific theorizing and exploration, including the application of the model to other domains [91].

#### 4.2. Representational Tools

As we have argued above, the way a model is constrained is crucial for its epistemic functioning; striving for accurate representation of some particular target system is frequently less helpful if the goal is to tackle some more general question, as is often the case with modeling. In such tasks, minimal and unrealistic models may be explanatorily useful: such models may isolate some hypothetically relevant, or difference-making features for particular patterns of interest [92–94]. Moreover, the use of mathematical and statistical methods entails simplification and unification as well [95].

In contrast to the representational approach that focuses on the general and abstract features of the relationship of representation, the artifactual approach emphasizes the concrete, workable dimension of models rendered by various representational tools, such as differential equations in the case of the Lotka-Volterra model. The concrete workability of models explains how scientists can learn by building and manipulating them [81]. For instance, Volterra's ability to draw important results from a highly idealized hypothetical system shows that in order for models to be epistemically useful, they do not need to correspond more or less accurately to real-world systems and processes.

This learning process is facilitated through articulating different kinds of relationships within a model with some particular representational tools, concretely manipulating them, and reconfiguring the model in view of further questions. Such work can lead to various kinds of explanations, predictions, and theoretical results, and may contribute to novel experimental designs and the construction of artificial and synthetic systems [96].

The fact that the epistemic importance of the concrete workable dimension of models has not received due recognition can partially be traced back to the tendency of treating models as abstractions. Such a tendency is understandable given the importance of mathematical and computational modeling in contemporary science. Once models are considered as abstract entities, likening them, or at least comparing them, to mental models seems an easy step to take, as we have seen above. Such a step should be resisted, however. The concrete workable dimension of models does not boil down to their material aspects only, it also applies to mathematical modeling as the case of the Lotka-Volterra model shows.

Most of Volterra's papers on biological associations are highly technical mathematics, consisting of the study of the mathematical properties of the Lotka-Volterra model and its variations. In other words, the differential equations provided Volterra the workable dimension of the Lotka-Volterra model, and the study of these equations gave him several results that could be given a biological interpretation. He would not have come up with these results had he simply mentally conceived the predator-prey system: the differential equations provided him a representational tool to access the dynamics between the two populations.

The representational tools employed in modeling typically consist of various symbolic or semiotic devices (mathematical, iconic, diagrammatic etc.) that serve as vehicles for conveying different kinds of content. However, these vehicles need to be embedded in representational media that furnish the material means with which representations are produced and manipulated (such as ink on paper or digital computer in which simulations are run) [18,87,96,97].

The representational media and their materiality play different epistemic roles depending on the type of model in question that has led to the perception that some models, such as mathematical models, are inconcrete, whereas other models, such as scale models, are concrete. But on closer inspection, such a distinction between concrete and inconcrete models tends to lead astray. For instance, there is accumulating evidence that the perceptual and sensorimotor engagement with external mathematical representations is crucial for

mathematical reasoning over and above them functioning as mere scaffolds for mnemonic and communicative tasks [98,99]. On the other hand, the Phillips-Newlyn model, a hydraulic model of a macroeconomy in which colored water flows and accumulates in a system of tanks and channels, does not reduce it to its material embodiment. As such, it would hardly be interpretable as a model, let alone an economic model. Instead, it gives a concrete form to the conceptualization of the economy in terms of stocks and flows that has a long history in economic theorizing [100].

#### 4.3. Representing and Justifying

It may seem puzzling that the artifactual approach seeks to explain the epistemic value of modeling without invoking representation, yet emphasizes the importance of representational tools. No contradiction is involved as representation in the sense of establishing a relationship between a model and a real-world target system should be distinguished from representing something *within* the model.

Representation in this latter sense refers to the use of representational tools to convey some content that is a precondition for claiming any representational relationship between a model and some external target system. Such distinction between these two notions of representation is embedded in the recent philosophical literature, where modeling as an activity of building and studying models is distinguished from establishing a representational relationship between a model and a target system. For instance, Weisberg [8] argues that the practice of indirect representation distinguishes modeling from those theoretical strategies that rely on abstract direct representation. Modeling, Weisberg claims, is engaged in indirect representation as modelers are primarily interested in studying their models, before trying to relate them to some real-world, or merely possible targets. Indeed, apart from providing possible explanations of the actual states of affairs, models also enable inferences concerning unactualized possibilities [87,96,101]. Such modal reasoning constitutes one of the main ways in which models are used in scientific practice [102].

Regarding the modal dimension of modeling, the artifactual account approaches the question of justification through model construction: a model is constructed for the purpose of probing theoretical and empirical consequences. Thereby, it becomes necessary to independently justify any kind of representational relationship (if only because of underdetermination). The fact that some models are used as representations does not provide justification for model-based results in and of itself. Although, part of the justification is already built-in due to the previously established theoretical, empirical and representational resources used in model construction [103]. The already established use of differential equations, and the mechanistic approach of isolating the components and their interactions, in addition to the observations on fluctuations in fish populations were resources already built-into Volterra's model. Due to these pre-established resources and knowledge, the relationship of representation is not pivotal for explaining how models are able to generate knowledge: it is not needed to connect a model to the empirical world as the connection is already partially built-in.

Finally, it goes without saying that in order to establish the external validity of a model, more is needed than consistently analyzing the built-in connection from successfully certified models. Such external validation in work-in-progress models typically proceeds by triangulating different epistemic means: other models, experiments, observations, and background theories. These processes of triangulation are often not easily recognizable due to their complex and indirect nature. Justifying models does, therefore, not happen through individual model-target comparisons as, e.g., the representational approach would have it, but rather by rigorously questioning models, even at the level of research programs, being distributed in terms of time, place, and epistemic labor.

## 5. Future Challenges and Implications

Equipped with the notion of models as epistemic artifacts, we turn in this section to two concrete examples, where a more theoretically consistent approach to modeling would have strengthened the already valuable educational implications. In our examples,



science education researchers implement straightforward empirical strategies according to the notion of models as artifacts, while such an approach has been less prevalent in philosophy of science. Nevertheless, these science education studies tend to set the concrete representational tools (e.g., sketches) aside, turning to discuss the mental models of students, as if a direct connection between them and the students' concrete modeling products could be established by the researcher in some unproblematic manner. In contrast, and in line with the artifactual approach, we emphasize that science education should focus on the epistemic value of concrete products in investigating the system of interest.

### 5.1. Model-Based Learning and Reasoning

As an important next step towards a better mutual understanding of model-based learning and reasoning, we propose below how to clarify the connection between the empirical studies' results, and their respective theoretical frameworks by drawing on the insights of this paper.

First, it would be helpful to focus on whether or not a learner was able to refine iteratively, and in a justified manner, concrete model objects (by sketching, modeling clay, etc.). In this regard, the question about the adequate rendering of canonical scientific knowledge appears to be of secondary importance. Yet, such an approach may appear unsatisfying at first: what scientist would give credit to a learner who gives justified, yet evidently false explanations about the behavior of a target system? It might seem that useful representations should not include disproven assumptions, at least within learning environments. Nevertheless, a learner may eventually be able to confront the experienced scientist/teacher with cases where hypothetical speculation is an intrinsic part of daily scientific business. Moreover, the learner may wonder why atoms are described as identical to tiny solid spheres in every introductory chemistry lecture, when the scientific community *knows* that this is not the case. When viewed from the artifactual perspective such assumptions do not appear so baffling, as they highlight the question-oriented character of modeling, providing thus a reasonable, though underappreciated, starting point for science classes [104].

Second, carefully choosing an appropriate target system presents challenges of its own. It does matter whether a learner either works on how introducing a species into a biotope affects the population of another species and comes up with a numerical association by counting and extrapolating, or tries to find a mechanistic explanation of ice maintaining its temperature while melting during heat supply. Both tasks can be approached through modeling, yet they are fundamentally different in terms of their underlying goals, i.e., numerically predicting or mechanistically explaining the target system. The situation gets even more complex if, contrary to the purely predictive goal, one inquires about the mechanisms that lead to the influence of one species on another, e.g., a predator-prey relationship or a displacement of another population due to an advantage in reproduction. Likewise, associating heat supply to state transitions and making predictions without asking for submicroscopic mechanisms is in itself valuable [105], highlighting the paramount importance of the question to be asked for any modeling activity. Thus, it is crucial to explicitly distinguish whether the aim of modeling is to present what is currently accepted as *being the case* in the field [106], pp. 141, or whether the focus is on practicing to think about and test the consequences of *what if something were the case?* [41]

### 5.2. Models and Subject-Specific Content

Inconsistencies of subject-specific models are rarely explicitly addressed in science education research [107], and, if discussed at all, they are approached within the context of multiple modeling [108–110]. However, presenting to a learner multiple models of a certain target system (e.g., Bohr's model vs. Lewis' structures) does not inform the learner when it is appropriate, e.g., to refer to electrons as particles circling around an atomic core, in contrast to electrons as fixed bonding pairs. The models do not reveal, in and of themselves, to what end and under which circumstances they were constructed, and what seems even worse from the learner's perspective is that they seem not to be true at the same time. In

this regard, learners and teachers alike should be encouraged not to suppose that they could perfectly state how unobservables, or other lesser known phenomena, are structured: multiple models of the same target systems should be regarded as a normal phenomenon in scientific research. Consequently, teachers, learners, and researchers should focus on the modal dimension of modeling, seeking plausible estimations, fruitful depictions, and how-possibly explanations. We were not able to identify such a consistent modal focus within the investigated studies.

We hereby turn to vindicating the lentils and beans model to a certain degree: if students work with this representational vehicle in response to a relevant research question, they can learn about chemistry as a matter of course. For example, if the bean-lentil demonstration was used to explain volume contraction, how could the structural relationship between the demonstration and the target system be justified in the first place? If we did not have any other evidence for such a relationship, we could adopt a question-oriented approach: *what if* the lentils and beans were structurally equal to water and ethanol particles? Subsequently, experiments would come into play and different liquids could be mixed and their behavior documented. Fortunately, in the sense of fostering model-based reasoning, mixtures exist that show a volume expansion, which falsifies the assumption of smaller particles fitting into the gaps between the larger particles as a general principle. That falsification could potentially lead to a more sophisticated reasoning activity that makes use of students' artifacts. These artifacts, in turn, could be integrated into standardizable frameworks under current development, e.g., stepwise procedures for the modeling of target systems in chemistry classrooms [15]. However, teachers and researchers should be careful about their presuppositions of unobservables; which of them appear to be resolved, and which of them side-stepped, via an over-simplified representation. While models as epistemic artifacts are constructed by representing what could plausibly, or possibly, be the case, and are thus able to convey scientific content [111,112] that does not yet justify supposing that they would accurately depict the structure of their target systems—as a representationalist would have it. A little sphere is not structurally equal to a molecule.

## 6. Conclusions

We have claimed that scientific reasoning can usefully be viewed as a question-oriented investigation. Modeling provides a prime example of such an activity. We have suggested that an explicit and reflective discussion of models as artifacts serves to prevent a relapse into viewing models as straightforward, uniquely determinable representations of target systems. We have observed in science education research a conflation of mutually exclusive epistemological accounts of models and representation, i.e., adhering to both pragmatist and structuralist perspectives. If a researcher refers to models as constructed tools, it is difficult to maintain a representational dyadic model-target relationship as a unit of analysis. Modeling submicroscopic mechanisms for explaining or predicting the behavior of, e.g., chemical target systems is a case in point. As we have shown, straddling between the pragmatist agent-based and the representational similarity-based and structuralist approaches to modeling breeds inconsistencies both on the theoretical level and between the theoretical definitions of models and the interpretation of empirical results.

Consistently understanding and explicating models as artifacts is helpful since it fosters an understanding of science as being revisable by keeping the focus on the interrogative, uncertain, and fallible nature of scientific reasoning. Thus, the studied target systems can be worked on with models as metaphorical magnifying glasses, hammers, or screwdrivers. Consequently, the artifactual approach shifts the focus of the discussion of scientific modeling within science education research from accurate representation into the learning of how to do science. Moreover, since the artifactual approach views any representational relationships between models and some real-world targets as contingent scientific achievements, it prompts researchers and teachers to reflect on the assumptions they make about target systems.

Finally, we find plenty of room for a dialogue between philosophy of science and science education research, a dialogue that is already happening. The link to teaching

makes science education research a worthwhile area of study for philosophers of science: philosophy cannot be considered just a source for trickling down theoretical ideas to empirical sciences. Especially practice-oriented philosophers of science are interested in what scientists think and do to gain knowledge about the world, and for this task, they need case studies and empirical research. Science education researchers are uniquely positioned to do just that: studying and conveying scientific reasoning at different levels of teaching, learning, and researching. Therefore, we advocate a fruitful and critical discussion between philosophers of science and science education researchers concerning their theoretical presuppositions and definitions, addressing also the question of how to plan and/or revise empirical studies on the basis of such reinvigorated mutual understanding.

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## Abbreviations

The following abbreviations are used in this manuscript:

NOSI Nature of Scientific Inquiry

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