Chapter 2
Semantic Views on Models: An Appraisal for Science Education

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2.1 Introduction

The importance of models in scientific activity can hardly be overrated; indeed, current philosophy of science has recognized that

> [s]cientists spend a great deal of time building, testing, comparing and revising models, and much journal space is dedicated to introducing, applying and interpreting these valuable tools. In short, models are one of the principal instruments of modern science. (Frigg & Hartmann, 2012)

The contemporary depiction of science as a model-based enterprise provides theoretical foundation to understand the role that scientific models are assigned in science education; such foundation are also crucial for the notion of modeling competence (Chap. 1), defended in this book. At the same time, models used in science classes at different educational levels are considered "an integral part of the understanding of the nature of science […], effective means for teaching scientific literacy [and] effective tools for teaching [science] content knowledge" (Krell, Upmeier zu Belzen, & Krüger, 2012, p. 2). In addition, the ability to effectively use models for specific purposes in specific contexts coupled with a robust understanding of such use is beginning to be considered one of the key aims of science education.

In tune with this perceived importance of modeling competence in science and in science education, meta-theoretical analyses of science have been devoting careful attention to the nature and use of models for six decades now:

> Given the ubiquity of models as well as their variety in form and content, major [philosophical] questions that arise from model-based scientific research concern the nature of

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> models, their relationship with real-world phenomena, and their reliability as a source of knowledge. (Sanches de Oliveira, 2013)

In science education, there is also "intense research […] using models and modeling" (Chamizo, 2013, p. 1616) along different lines, but if we aim to understand, investigate, and foster modeling competence in science teaching, there is an unavoidable prerequisite of a theoretical nature: We need to ascertain which views of all the former issues about models – views coming from the many historically or currently available conceptualizations of models in the philosophy of science – can be valuable for investigation, innovation, curriculum, teaching, evaluation, and teacher education (cf. Grandy, 2003).

Some authors in our field (cf. Adúriz-Bravo, 2013; Chamizo, 2013; Develaki, 2007; Izquierdo-Aymerich, 2013; Koponen, 2007) have tackled the previous question by arguing in favor of a 'semantic view' on scientific models, coming from the so-called 'semanticist family' – a philosophical tendency from the last quarter of the twentieth century. But there are a wide variety of semantic views: How can we characterize them in order to generate *educational* criteria to compare and choose?

With all these considerations in mind, the aims of this chapter are: (a). to discuss what counts as a semantic conception of a model in science and in science education, (b). to distinguish between different semantic conceptions available in recent and contemporary philosophy of science, (c). to locate these conceptions within the various epistemological characterizations of scientific models that have been produced in the history of the philosophy of science, (d). to identify 'transpositions' of the semantic views on models circulating in our research community of science education, and (e). to draw some inferences for the study of modeling competence.

2.2 Archaeology of the Concept of Model

Arising as an idea in the late medieval period, 'model' is a relatively recent construct (cf. R. Müller, 1983, 2009). Its origins and history are connected to the areas of architecture, design, and engineering (Ammon & Capdevila-Werning, 2017; Mahr, 2009), areas in which it has conveyed some sense of canonical measure that should be copied (cf. Mahr, 2009, 2011; Müller & Müller, 2003).

The initial conception of models, stabilized in the Renaissance, stems more or less directly from the technical developments of the Roman Empire. Thus, in ancient Greece, there was no full equivalent of this notion, which was covered by a wide range of terms: prototype, archetype, icon, image, paradigm, epitome, canon, metaphor, analogy, representation, allegory, and simulacrum, among a host of others (cf. Müller, 2000, 2004).

The term 'model' was derived from the classical Latin term 'modus.' 'Modus' and its diminutive 'modulus' were employed in the first centuries A.D. in a diversity of fields, such as music, rhetoric, and architecture (Müller, 2004, 2009). These words were used to describe the way something is or is done and, much more frequently, to refer to something that can be measured (Müller & Müller, 2003, p. 31).[1] The eventual convergence of these two complementary meanings of the Latin stem lies at the center of the current use of the idea of model in scientific activity. For instance, one of the early applications of the term designated a dressmaker's dummy, which was at the same time a *simulacrum* of a client's body and a *prototype* for the client's garments (Müller & Müller, 2003, pp. 32–35). Analogously, a scientific model –as we understand it in contemporary science – is a stylized capture of a phenomenon that serves as a mold or cast that is used to understand other phenomena.

During the two millennia of their prehistory and history, the concepts of module and model progressed toward emphasizing representational power, i.e. the capacity to stand for something else –the entity being modeled (cf. Mahr, 2011; Müller, 2004). A model came to be seen as an exemplar entity that serves as a measure to shape and bind the existence of other entities. In its current sense, it *re*presents (i.e. presents again: *acts in the place of*) a whole abstract class even when no member of such class (no 'specimen') is physically present.

According to the previous analysis, the concept of model was readily available during the institutionalization of the philosophy of science as an academic discipline. In spite of this, such a concept is notably under-represented in the literature of classical positivism, the 'orthodox' epistemology of logical positivism, and the ensuing 'received view' of the 1950s and 1960s (cf. Mahr, 2009; Müller, 2004).[2] This shows that models – unlike theories – were not regarded until very recently as a key element in philosophers' understanding of the functioning of science (Chap. 1).

During the whole nineteenth century and the first half of the twentieth century, the canonical conceptualization of models was based on a 'derivative' definition of the concept, influenced by developments of logic and meta-mathematics (cf. Suppes, 1961). The usual practice was to define models as derived from theories: a model (*of a theory*) was considered to be "a structure constructed by means of the theory's concepts" (Moulines, 2010, p. 20). Thus, a pre-existing theory (a completely formal object) could be later 'interpreted' in a particular domain of experience, and such a domain subsequently became a model of the theory's axioms.

In the second half of the twentieth century, more sophisticated definitions of 'model' ensued. Philosophers' attentions were driven toward scientific models mainly as a result of major changes in scientific activity, which led to a 'discrepancy' between the actual practices of science and the reconstructions of such practices circulating in the philosophy of science, which were still *theory*-based (cf. Sal, 2013, pp. 29–56). Thus, models became the most appropriate form of representation of natural or artificial systems, and this brought the theoretical category of model to the forefront of philosophical meta-analyses.

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[1] In English, we find that 'modality' (a particular mode in which something exists) and 'modularity' (the quality of being composed of standardized units) are derivatives of these two separate meanings.

[2] e.g. in Carl Hempel's famous textbook, *Philosophy of Natural Science* (Hempel, 1966), scientific models are not mentioned as an important meta-theoretical concept.

2.3 Meta-theoretical Approaches to Models in the Twentieth Century

The historical evolution of philosophical 'models on models' during the twentieth century was intricate and eventually led to a proliferation of conceptualizations in the last few decades (cf. Frigg & Hartmann, 2012; Moulines, 2010; Müller, 2009; Sal, 2013). Three of these conceptualizations of scientific models will be compared here through a non-technical reconstruction of their definitions of model using the much more intuitive notion of 'example.'

'Example' has two distinguishable meanings: It can be understood as an instance (constituting a mere specimen) or as an epitome (setting a general pattern). An example understood as an instance, case, illustration, occurrence, specimen, and so forth, is an element from a class or a kind, merely *conforming to* the 'rules' that determine and delimitate such a kind. Thus, we could say that "an apple is an example of fruit." In turn, an example understood as an epitome, exemplar, paragon, embodiment, pattern, and so forth, is an element that stands out in its kind and is selected in terms of its fitness *to be imitated*. Thus, we could say that "Mother Teresa of Kolkata is an example of compassion." In this second sense, examples are seen as more abstract, idealized, and prototypical than in the first sense (Adúriz-Bravo, 2013).

In the conceptualizations pertaining to logical positivism –the first 'professional' school of philosophy of science– and to the so-called 'received view' that subsequently settled after the dissolution of the Vienna Circle (i.e. during the lengthy period spanning from the 1920s to the 1970s), a scientific model was identified with *any* example of a theory (i.e., a mere instance that satisfies the mandates of that theory –typically, its laws). This reduction of models to more or less irrelevant parts of theories gave way, for instance, to the proposal "to collapse the distinctions between models, theories, analogies, and to take all of these, and more besides, as species of the genus representation; and to take representation in the most direct sense of image or copy" (Wartofsky, 1966, p. 1). In extreme cases of this reductive tendency that was consubstantial to the *syntactic* approach to theories, models were "superfluous additions [to those theories] that are at best of pedagogical, aesthetical or psychological value" (Frigg & Hartmann, 2012).

In the 1950s and 1960s, in the context of an emerging 'new' philosophy of science and especially through the works of Thomas S. Kuhn and some of his contemporaries, a first crevasse to this analytic and formalist conception of models opened. A scientific model began to be portrayed as a *paradigmatic*[3] example of a theory, serving as a theoretical epitome worthy of imitation for problem solving during 'normal science.'

[3]The adjective 'paradigmatic' comes from the Greek term for 'example': a paradigmatic example is thus an 'exemplary example', i.e. example in the second sense. Kuhn advocated for the use of the category 'exemplars' (as a noun) to denote models.

A model à la Kuhn can be seen as a particular socio-historical achievement of a scientific community, outside scientists' heads, contained –in a very stylized version– in disciplinary textbooks, and embodying operative rules to be followed (Nickles, 2003). This idea of model, which stresses its analogical nature, was extremely influential until the 1980s.

Finally, in the last quarter of the twentieth century, a semantic conception of scientific theories (which had noteworthy antecedents from the early 1950s, see Suppe, 1977) gained momentum, rapidly shifting the interest from form to content, from structure to meaning. Within this new theoretical framework, a scientific model began to be identified with an *intended* example of a theory (i.e., a phenomenon that the theory itself was purposefully conceived to account for). This idea that *all* models are "models-for" is fundamental to the conception of modeling competence presented in this book.

Such a semantic characterization of models purported to offer a 'third way' between the received view and the new philosophy of science, explicitly welding together the Kuhnian reconstruction of models as exemplar cases with the conservative analytical requirement that they can all be represented in (semi)formal ways, formulating them as generally and as abstractly as possible.[4] This 'hybrid' semantic view of models was soon shown to be "the only serious contender to emerge as a replacement for the received view analysis of theories" (Suppe, 1977, p. 709) and eventually became the most widely held view among philosophers of science, at least in the communities of strong Anglo-Saxon influence (Frigg, 2006; Suppe, 1989). It is the contention of the author of this chapter that a semantic approach to models is the most useful for the idea of modeling competence.

2.4 Semantic Views of Models in the Late Twentieth Century

From this point on, the umbrella title of 'semantic views of models' is used to encompass a large number of relatively recent characterizations of the concept of 'scientific model' proposed by a range of philosophers that can be situated in what has come to be called the *semantic conception of scientific theories*, by opposition to the hegemonic syntactic conception (cf. Portides, 2005). Semantic views in a broad sense have existed since the 1950s (with the early structuralism of Patrick Suppes and even previous meta-models influenced by the Polish logician Alfred Tarski); in a strict sense, the term refers to the well-known 'model-based views' on science that hail from the 1980s and 1990s.

The following three objectives will be pursued: a. to ascertain some common traits shared by the diverse semantic views of models, especially the most recent ones, b. to make a few distinctions between the theoretical frameworks of the best-known semanticist philosophers of science of the last quarter of the twentieth

[4] This strategy of recovering the best of each of the two preceding periods constitutes a key feature of the semanticist approach (Lorenzano, 2001).

century: Ronald Giere, Frederick Suppe, and Bas van Fraassen, and c. to briefly point toward the existence of conceptualizations of models that can be considered semantic (or post-semantic) but are cited much less often in the science education literature (e.g. proposals by Roman Frigg, Margaret Morrison, Michael Weisberg).

The lists of commonalities and differences between the semantic views that are presented here have emerged from previous work of elucidation and argumentation and from literature reviews (cf. Adúriz-Bravo, 2013; Ariza, Lorenzano, & Adúriz-Bravo, 2016); such work has been based on different sources: textbooks of philosophy of science written by authors with a 'bias' toward semanticism (e.g. Díez & Moulines, 1997; Rosenberg, 2000), reviews of the emergence of the semantic view (e.g. Díez & Lorenzano, 2002; Sal, 2013), general overviews of the field of model studies in academic books by semanticists (e.g. Giere, 1988; Weisberg, 2013), and 'transpositions' of the semantic approach made by researchers in science education (e.g. Izquierdo-Aymerich, 2000; Passmore, Gouvea, & Giere, 2014).

Working on all these sources, at least five 'common pillars' of all semantic views on models can be recognized[5]:

1. *The focus of theory meta-analysis is displaced from syntax to semantics.* The philosophical interest of the semanticist family has been placed on how scientific theories give meaning to the world and make sense to their users. Attention moves from the structure of theories to the functioning of models. The concept of model itself and all its related constructs that this new approach considers essential for meta-analyses (e.g., truth, predication, correspondence, homology, meaning, use, context) are markedly semantic (Guerrero Pino, 2000). Most of the first post-classical (1945–1975) analyses on scientific models are directly shaped by Tarski's semantic theory of truth (Glennan, 2000). Additionally, the more contemporary representational, cognitive, or mediation-based approaches to the concept of model (1975-today), which are overtly model-theoretical, fully embody the 'semantic turn' in the philosophy of science, and thus move much closer to the theses in the 'second Wittgenstein' of the *Philosophische Untersuchungen*.
2. *Empirical theories are, at their very fundamentals, families of models.* From the point of view of philosophical analyses, a scientific theory, even though it is a complex entity with various components, can be fruitfully characterized as a family of models (cf. Suppe, 2000). The very identity of a theory could be in principle determined by that family (or e.g. class, set, population, collection, cluster). A theory defines, through a diversity of mechanisms, the family of its models; accordingly, *presenting* a theory (for philosophical and also most probably for educational purposes) mostly means specifying its models, which are understood as structures (van Fraassen, 1980, p. 64).
3. *An empirical theory admits 'equivalent' presentations through different symbolic resources.* Semanticists do not assume the primacy or superiority of some of

[5] Readers can compare this presentation with other lists of 'common elements' shared by the members of the semanticist family: Díez, 1997; Echeverría, 1999; Estany, 1993.

these forms of theory (re)presentation (e.g., the axiomatic, which was the preferred in classical philosophy of science) over the others. In this sense, non-rigidly formalized knowledge can be considered theoretical and can be expressed ('defined') with very different languages –scale models, drawings, paradigmatic facts, cases, metaphors, gestures, etc.– conserving their explanatory power (Izquierdo-Aymerich, 2007).

4. *Empirical theories explicitly intend to relate models to the real world.* A theory unequivocally states that there is a substantive relationship between the models that belong to it and the phenomena it intends to 'cover.' The theory 'empirically asserts' that some phenomena are adequately accounted for by its models, and such an assertion, which has a linguistic nature, can be deemed (approximately) true or false. In turn, models are seen as non-linguistic items that are

> true by definition. An ideal gas is by definition just what behaves in accordance with the ideal-gas law. [Thus, the] empirical or factual question about a model is whether it 'applies' to anything closely enough to be scientifically useful –to explain and predict its behavior. […] Once we specify [what is meant by] 'well enough' […], this is a hypothesis […]. A theory is a set of hypotheses claiming that particular sets of things in the world are satisfied to varying degrees by a set of models which reflect some similarity or unity. (Rosenberg, 2000, p. 98)

5. *Empirical theories contain the phenomena explained by the models.* The semanticist characterization of theories leaves behind the neo-positivistic metaphorical portrayal of a theory as a 'safety net' connected by poles to the floor and projecting its shadow onto it (i.e., a network of formal, axiomatic elements and relations that only afterwards are 'projected' onto reality through interpretation rules; cf. Sijuwade, 2007). In opposition to such a metaphor, semantic views include the class of theoretical models *and* the 'intended applications' of such models (i.e., the set of real systems that these models pretend to account for) within the theory. In this conception, models can be seen as idealized, reconstructed, or interpreted facts:

> Models show in which phenomenological context theoretical entities make sense and how they are used to intervene in it and to explain what happens. The set of theoretical models can be described through axioms and entities (this is what textbooks usually do), but neither the former nor the latter have meaning without the phenomena from which they emerged; thus, [theories] are action, not only mental representation or language (Izquierdo-Aymerich, 2013, p. 1636).

Of all the previous commonalities in the semantic portrayal of models, the first and fourth ones are the most in tune with the idea of modeling competence as it is approached in this book. On the one hand, Bernd Mahr's analysis of 'model-being' (Chap. 1, providing the foundation of the framework for modeling competence: FMC) emphasizes *pragmatic* aspects that are typical of the semantic turn: it is the *users* who identify an entity as a model through a process of constructive operations ("relationships of creation") of clear semantic nature:

> An object M is not a model in itself, but only if it is conceived of as a model by a judging subject. Through the judgment by which the object M is conceived of as a model, M is placed in a context in which, according to the judging subject, M presents itself as a model (Mahr, 2011, p. 371).

On the other hand, the seminal conception of modeling competence (cf. Krell, Upmeier zu Belzen, & Krüger, 2016) that is being fully developed in this book consistently highlights the process through which models become models-for-something (the process that Mahr calls the 'application'). The FMC locates such a process at the highest level of competence that students (and teachers) should ideally achieve. The semantic pretension that models are created to *account for* systems, an idea that is theoretically captured in the notion of models as intended examples, is in accordance with these ideas.

As stated at the initial paragraph, it is also possible to identify several very notable differences between the various semantic 'versions' inscribed in the semanticist family. It might be useful to organize these differences into the following categories (Ariza et al., 2016): a. the ways in which the notion of model is formally captured; b. the ways in which models and model classes are identified; c. the ways in which the 'pieces/portions of reality' (we can call them, for the sake of simplicity, 'real systems,' see Ruttkamp, 2002, pp. 90–140) that theories intend to account for are characterized; d. the ways in which these real systems are related to models; and e. the constituents of a scientific theory beyond its family of models.

For the sake of space, only category d. will be developed here as an illustrative example of the disagreements that exist among authors within the semanticist family. Afterwards, we present the three quite distinct theoretical conceptions of the relationships between models and systems held by van Fraassen, Suppe, and Giere –which are shaped by their commitment (or lack thereof) to a realist stance. Van van Fraassen (1980) talked about *embeddability*: the different actual and observable aspects of a phenomenon are 'saved' by a single model allowed by the theory. Suppe (1989) resorted to the idea of *homomorphism*, a 'mapping relationship' between a real system and model that can be established within the scope of the theory (i.e., disregarding the influence of variables that are not contemplated in such a theory). Giere (1988) introduced a relationship of *similarity* of type and degree between model and system, which was indebted to Wittgenstein's notion of 'family resemblance.'

Additionally, in order to demarcate between various semantic conceptions of models, the "precise nature of [the] entities called models" (Lorenzano, 2010, p. 46), a most noteworthy point of divergence between semanticist philosophers of science, is also very useful. The definition of theoretical model (in empirical sciences) used by the different authors in the semanticist family could be arranged from the earliest, most formal approaches, resorting to model theory, through conceptions analogically drawing from the natural sciences (considering models as 'phase-' or 'state-spaces,' as van Fraassen or Suppe did: cf. Thompson, 1989, Chap. 5), to much more informal characterizations (e.g., the one by Ronald Giere; see Ariza et al., 2016; Lorenzano, 2010). In all the aforementioned cases, nevertheless, more or less close relationships to classical conceptions of models in mathematics, meta-mathematics, and logic are conserved (cf. Downes, 1992). Of all these 'models of models,' the ones that are more flexible in setting conditions for an entity to be a model seem the most suitable for a model-based science education and in order to go deeper into the notion of modeling competence.

The state of affairs described above is something that could be rapidly changing in the twenty-first century, when even more sophisticated semantic reconstructions of models are emerging. Indeed, more flexible and theory-independent depictions of what models are and how they work are available (e.g. Frigg, 2006; Herfel, Krajewski, Niiniluoto, & Wójcicki, 1995; Morgan & Morrison, 1999; Suárez, 2003; Weisberg, 2013). New meta-models assign to models the function of connecting the theoretical and empirical realms. Models would then 'mediate' between these realms, and it would not be possible to completely reduce them to concrete items or to linguistic enunciations, conserving a high degree of epistemic autonomy.

In order to explain these emerging conceptions of models as theory-independent mediators, it is useful to resort to the 'clementine analogy' (clementines being a hybrid of oranges and mandarins). When a clementine lies next to an orange, it looks like a small, dried version of the latter; when lying next to a mandarin, the clementine appears to be a particularly big, turgid specimen thereof. Analogically, models can be imagined as ontological hybrids participating in the 'fabric' of theoretical frameworks and of real systems. According to this view, a model would act at the same time as a well-formed applicative restriction of theoretical principles and as an idealized, concept-laden portion of the world.

The general notion of model incorporated into the FMC for this book, drawing on ideas by Stachowiak (1973) and described in Chap. 1, finely adjusts the 'mediating' conception, while being less radical concerning the *ontological* nature of models.

2.5 Semantic Characterizations of Models in Science Education

The starting point here is the recognition of two consensuses within our community of science education. First, even though the notions of model and modeling have been implicitly present for some time in the science curricula of all educational levels, it is only recently that curriculum designers, science education researchers, and science teachers have begun to advocate for an explicit treatment of the meta-theoretical concept of model in science teaching (cf. Gilbert & Boulter, 2000; Harrison & Treagust, 2000; Justi & Gilbert, 2002; Khine & Saleh, 2011). Second, academic production on models and modeling in science education has reached significant levels of depth and sophistication, but, in spite of this, our community still needs further discussions of fundamental issues about the epistemology of models. We may have adopted a standard definition of the construct of model –of neo-positivistic filiation– that has barred more careful elucidation around some basic issues (cf. Johsua & Dupin, 1993; Koponen, 2007).

In addition to this, in the academic field of science education, there seems to be a very timid materializing of a new portrayal of models for research and practice that –with more or less awareness from us science education researchers– can be located in the arch of ‘model-based’ or ‘model-theoretical’ conceptualizations (e.g. Gouvea & Passmore, 2017; Grandy, 2003; Justi, 2006, 2009; Koponen, 2007; Oh & Oh, 2011). We could thus talk about the emergence of a ‘model-based science education’ (Adúriz-Bravo, 2010). Within this emergent approach to research and innovation that focuses on models, modeling competence could be considered a new and promising line.

Semanticism still remains a philosophical school that is far from being understood within our discipline; hence, carefully reviewing what counts as a semantic view on models and drawing implications of such a view for science education continues to be a necessary task. In addition, the existence of a variety of semantic understandings of models in the community of the philosophy of science makes it complex to straightforwardly pick out a ‘definition’ that is ready for educational use. This also holds for the discussions in this book around the new idea of modeling competence.

Authors in science education have undertaken the aforementioned review by looking into some fundamental epistemological aspects of models and modeling (e.g. Erduran & Duschl, 2004; Izquierdo-Aymerich, 2004; Johsua & Dupin, 1993; Lombardi, 1998, among many others). Of all these antecedents, it may be interesting to focus on three texts—by Chamizo (2006), Oh and Oh (2011), and Krell et al. (2016). In these texts, the authors explain what they regard as the most important issues around models for the purpose of educational discussion, and they do this from theoretical positions that can be considered more or less semantic.

In his article, Chamizo (2006) identified what he considers the eight “least controverted” (p. 476) characteristics of scientific models: (1) models are representations (of, e.g., objects, systems, phenomena, processes); (2) models are instruments that can provide an answer to scientific problems; (3) models constitute analogies of the phenomena they represent; (4) models differ from reality because their construction follows a particular aim; (5) models are constructed by compromising between the similarities and differences that they have with their represented reality; (6) models are developed and changed along history; (7) models undergo a process of acceptance in the scientific community; and (8) models can be classified into types.

In turn, Oh and Oh (2011) presented “an overview of the nature of models and their uses in the science classroom for science teacher educators and subsequently for science teachers” (p. 1111). Through an analysis of specialized literature and empirical research on different groups of experts, they identified “five subtopics concerning the nature of models and modelling” (p. 1111), and, similar to Chamizo, they found some consensus among philosophers of science and science education researchers surrounding such subtopics: (1) models are usually meant to refer to representations; (2) the usual purposes of models are to describe, explain, predict, and communicate; (3) scientists use a multiplicity of models when engaged in scientific problem solving; (4) models are developed and changed in history; (5) models are usually used in science teaching with the justification that “external presentations of visual representations provide support for constructing and reasoning with internal representations” (Oh & Oh, 2011, p. 1120).

Finally, Krell et al. (2016) identified five important aspects that should be taken into account when reflecting on models and modeling: (1) models are *of* and *for* something; (2) scientists use a multiplicity of models for the same phenomenon; (3) models serve different purposes (to describe, explain, and hypothesize: Krell et al., 2012, 2016; Krüger, Krell, & Belzen, 2017); (4) in scientific practice, models undergo rigorous testing; and (5) models are developed and changed along history.

Practically all the characteristics, topics, or aspects (collectively, 'facets' of model meta-analysis) that were proposed in the previous three texts have been incorporated into the theoretical FMC. Such facets cover issues such as the nature, use, and evolution of scientific models, the processes of formulation and evaluation of such models, and their purposes and value in science (see Grünkorn, Hänsch, Upmeier zu Belzen, & Krüger, 2012).

2.6 Teaching Modeling Competence from a Semantic Perspective

As stated in the Introduction, many contemporary philosophers of science asseverate that modeling ('acting-with-models') is arguably the most important intellectual activity in contemporary science (cf. Herfel et al., 1995; Magnani, Nersessian, & Thagard, 1999). The idea of organizing science teaching around modeling has also gained momentum in research in science education (cf. Justi & Gilbert, 2016). But it can be contended that such an idea crucially depends on our conception of the nature of modeling competence in scientists' science and in school science. The following paragraphs briefly tackle the issue of the implications of infusing a semantic view of models in a competence-based approach to school scientific modeling.

What counts as 'modeling' when it is *understood as a scientific competence*? Just as with the construct of 'model', there are important theoretical disagreements around this issue. We can consider at least four main senses with which the idea of 'modeling' is used in science education (Adúriz-Bravo, 2012):

1. The creation of an original theoretical model to face the study of a phenomenon. In extreme cases, a model may be completely new with respect to the body of established knowledge in a particular historical moment; more commonly, it is new only from the point of view of the learners' knowledge base.
2. The process of subsuming a puzzling fact that is being investigated in the science classroom under an already available model that can account for it, in a process of *inference to the best explanation* (i.e., reasoning backwards).
3. The interactive adjustment of an established model after the emergence of new, unexpected, or anomalous elements during investigation.
4. The intellectual exercise of reconstructing well-known 'couplings' between models and facts in the context of learning the scope and use of a theory.

In the first comprehension of modeling competence proposed here, students, through scientific activities in school, can develop more or less innovative theoretical models in order to tackle 'scientific problem solving'; such models can be generated from previous models through analogy, combination, or refinement or they can also appear through rather intricate cognitive mechanisms (including: dreaming, illumination, and intuition; accident, coincidence, or serendipity). For this sense of modeling, undoubtedly very ambitious for science education, the semanticist analogy of theoretical models as maps to navigate a territory may be useful.

In the second sense of modeling competence, established models, available culturally, can be deliberately applied to the explanation of puzzling facts through very elaborate ampliative (e.g. abductive and analogical) reasoning. The aim of such modeling processes would be to show that, in some way, the facts to be explained are 'similar' to those models that are prospective candidates to explain them through the establishment of a case-rule relationship (Adúriz-Bravo, 2005). In this second sense of modeling, the semanticist insistence that models must be understood as "models-for" could be illuminating.

As for the third meaning of modeling competence, in the process of explaining families of phenomena in scientific research, new phenomena, observations, and results, more and better empirical data, additional theoretical knowledge, or new modes of representation and communication may force the need for adjustments in the accepted models; in this way, details, expansions, and corrections would be added, allowing models to be refined and improved. These iterative sequences may be captured by the semanticist idea that scientists continually evaluate whether their models satisfactorily account for phenomena.

Finally, a more modest –and yet educationally powerful– conception of modeling competence in the science classrooms of all educational levels is available in our discipline. It consists of understanding modeling as the process of reconstructing the established ('normative') linkage between facts and models. Although such a linkage is transparent in scientists' science, it certainly appears as new to students. Students, aided by the class group and the teacher, would put into action robust school scientific models in order to shed light on problems that are of interest to them and, at the same time, constitute the intended applications of those models.

According to this conception, the ultimate aim of modeling competence in science education would be that students use the models that they are learning in order to explain to themselves and to others some issues of interest in the natural world, aware that such an explanation already exists in science. In this last scenario, a fully semantic (as opposed to syntactic) approach to the process seems to be necessary. Additionally, a conception of models as epitomes that 'guide' new applications of knowledge may turn out to be appropriate.

In this last, albeit conservative, conception of modeling competence, theoretical models could be introduced with an explicit emphasis on their analogical nature, thus leading to learning about the *nature of models* (understood as what, in Chap. 1, is designated as a set of abilities to reflect on models and modeling). A learning goal –which complements 'pure' science content– would be to recognize that the extremely abstract way in which a scientific model of a phenomenon used in school can be described ensures the possibility to project it onto other phenomena under study, between which similarity is perceived. As Hernán Miguel stated:

> [An] abstract model can have two interpretations: one in which the abstract entities of the model correspond to [the model-for, taken as analogans] (...) and another in which the abstract entities are assigned [the meanings of the new model, taken as analogandum]. Evidencing this double interpretation of a same abstract model permits teachers to generate (in students) the idea that they can have structural knowledge of [a phenomenon] and that perhaps, within the limitations of the analogy, other [phenomena] could be well-represented using the same abstract model (Miguel, 1999, p. 95, translated).

In the semantic approach to modeling competence introduced in this chapter, and compatible with the more general characterization of such a competence in the rest of the book, school models are construed and taught as models-of and models-for at the same time (cf. Adúriz-Bravo, 2012, 2013; Giere, 1988; Gouvea & Passmore, 2017; Krell et al., 2016; Mahr, 2009, 2011). On the one hand, they are introduced as the abstract counterparts of the systems modeled in 'interventions' (observations, experiences, experiments, simulations); on the other hand, they are tested as exemplars in order to create new models that are more specific or more general and that can be meaningfully linked to the initial ones in 'families.' Together, these two epistemic processes, when enacted *and reflected upon*, constitute modeling competence as a whole.

Thus, modeling competence would imply the conscious use of scientific models as paradigmatic and intended examples: students would be acquainted with a theoretical model as a stylized case standing for a larger and more abstract reality and as a robust example of a type, thus setting a norm. For example, the 'school model' of a cell would serve in science teaching as a highly schematic version of something that can be 'identified' under a microscope and also as a blueprint (in the architectural sense) that guides our description, understanding, and manipulation of different cell types (e.g. neurons, liver cells, white cells, skin cells).

The notion of modeling competence proposed here can be understood as the testing of explicit hypotheses on the degree of adjustment between our ideas and our interventions. A 'new,' less dogmatic, scientific method could thus be introduced in the science classroom (cf. Adúriz-Bravo, 2008; Giere, Bickle, & Mauldin, 2006; Izquierdo-Aymerich, 2013); such a method would consist of making critical decisions about the 'convergence' between consequences derived from our theoretical ideas (after 'putting models to work') and data obtained from carefully planned observations and experiments. The aim would be to compare the results of these two coordinated sets of activities and assess the extent to which our ideas 'talk about the world' (see level III in Chap. 1).

According to this approach to modeling competence, school science would be analogous to scientists' science in an 'irreducible' epistemic aspect: Science students would work in a way that is similar to that of scientists, who

> use abstract thinking in a way that gives rise to a set of 'idealized facts' about which they speak using the entities that they define as 'theory,' [and such] facts (constructed with actions, representations and language) [become] the 'models' of the theories. (Izquierdo-Aymerich, 2013, p. 1636)

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