Chapter 3
A Framework for Modeling-Based Learning, Teaching, and Assessment

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3.1 Introduction

Interest in encouraging learners to engage in modeling is grounded in the premise that models help learners learn more robustly. First, models can facilitate an improved understanding of the behavior of systems (Crawford & Cullin, 2004; Hokayem & Schwarz, 2014; Maia & Justi, 2009; Nicolaou & Constantinou, 2014) by acting as intermediates between learners' efforts to describe and represent a phenomenon and their endeavors to interpret it. Second, by engaging in modeling-based learning, we can improve our ability to construct, revise, compare, evaluate, and validate models, all of which are important science practices (National Research Council, 2012; Nicolaou & Constantinou, 2014; Schwarz et al., 2009).

Many scientists, science educators, and philosophers consider modeling to be the backbone of knowledge construction with regard to systems and natural phenomena (Bunge, 1983; Chapman, 2000; Gilbert, Boulter, & Rutherford, 1998; Gilbert, 1991). Educational reform documents identifying the value of engaging learners in constructing and using models (National Research Council, 2012, 2013), also highlight the need to promote teaching interventions that are aimed at developing modeling competence. To accomplish this, it is important to support teachers with robust frameworks for teaching and assessment methods that are related to active modeling. Additionally, in this chapter, we will argue that the development of such frameworks, as well as processes for supporting and guiding teachers in their efforts to help learners engage with modeling, could contribute to overcoming the problem of the relative scarcity of modeling-based learning in schools (Duschl, Schweingruber, & Shouse, 2007).

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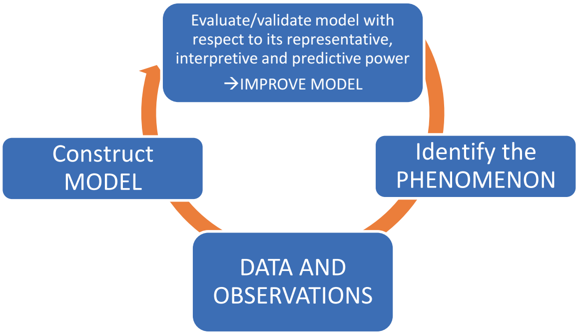
In this chapter, we present an approach for teaching science learning through model construction, refinement, and validation. We begin by describing the epistemological underpinnings and the rationale for a modeling-based teaching and learning approach that is designed to develop knowledge of natural phenomena. We proceed by describing the modeling-based learning framework (MLF) in terms of the modeling practices (model construction, model use, model revision, model comparison, and model validation) and the modeling meta-knowledge (knowledge about models and metacognitive knowledge of the modeling process) that emerge alongside the development of expertise in scientific modeling. We then present a process for identifying the attainment levels of each component of the modeling-based learning framework as well as examples of these attainment levels. Our core argument refers to the interconnectedness of the practical and epistemological aspects of modeling-based learning. On the one hand, the MLF seems to deviate from other frameworks for models and modeling. On the other hand, the MLF emphasizes implementation into meaningful learning and teaching practice in ways that have a positive influence on science teaching and learning. First, the MLF has the potential to help researcher-teacher teams bring out the nature of scientific modeling in the classroom. Second, it will facilitate more empirical research in this area by better informing both curriculum design and teaching practices with respect to how each aspect of the MLF can potentially be interwoven into teaching-learning sequences and also be assessed (Constantinou & Papadouris, 2004).

Science can be thought of as a complex and dynamic network of models that are interrelated through a system of theoretical principles (Constantinou, 1999). A model is the outcome of an application of a theory to a phenomenon. As noted by Upmeier zu Belzen, Krüger, and van Driel in the introductory chapter of this book (Chap. 1), there is no uniform definition of the concept of a model or the modeling process in the natural sciences. However, for communication purposes and as a basis for the development of the MLF, we assume that a *scientific model*[1] is an epistemological entity that represents a phenomenon (Giere, 1999, 2004; Hughes, 1997; Passmore & Stewart, 2002), provides the mechanism behind how this phenomenon operates (Berland & Reiser, 2009; Braaten & Windschitl, 2011), and can be used to make predictions about the future behavior of the phenomenon (Bunge, 1983; Hughes, 1997; Raftopoulos, Kalyfommatou, & Constantinou, 2005). This definition emphasizes the idea of a model as an external representation, it provides an interpretation of a phenomenon or system, and it can be used to predict the future behavior of the system. The *representational aspect* of the model is shaped by its constituent components (i.e., objects, variables, and processes). The *interpretive aspect* of the model is related to the provision of an interpretation that posits one or more mechanisms that underlie the observable behavior of a phenomenon. This can take the form of a story that elaborates on how a phenomenon operates and highlights

[1] It is important to clarify the idea that scientific models are different from mental models (Gentner & Stevens, 1983), which are Cognitive Psychology constructs that refer to "transient representations that are activated usually when one is exposed to a new situation and act as structural analogies to situations or processes" (Greca & Moreira, 2002, p. 108).

Fig. 3.1 The modeling-based learning cycle



the relationships between the objects, the variables, and the processes. Specifically, an interpretation provides one or more mechanisms and elaborates on how the phenomenon emerges from the mechanism(s). Finally, a model needs to have predictive strength by facilitating the formulation and *testing of predictions* for new manifestations of the phenomenon it represents.

Learning by modeling refers to the modeling practice and more specifically to the idea of learning through the construction, revision, and validation of models (Crawford & Cullin, 2004; Nicolaou, Nicolaidou, & Constantinou, 2009; Schwarz et al., 2009). Learning by modeling should be differentiated from learning with models (De Jong, Van Driel, & Verloop, 2005; van der Meij & de Jong, 2006). The latter denotes learners who are using previously constructed models with the aim of gaining insights into the phenomenon represented by the model. By contrast, learning by modeling is about constructing interpretive representations with predictive power (often in symbolic form).

Central to learning by modeling is the modeling-based learning cycle (Constantinou, 1999; Nicolaou et al., 2009), an iterative process that engages the learner in a continuous comparison of the model with the represented phenomenon (Fig. 3.1). The purpose of this comparison is to obtain feedback for improving the model so that it accurately represents as many desired details of the original system/phenomenon as required. It is also a cyclical procedure (Mendonça & Justi, 2014) that could involve the generation of models of various forms until the model generator finds one that successfully emulates the observable behavior of the system. Hence, the outcome of engaging in a modeling-based learning cycle is a series of successive models, usually ranging from more superficial versions to more scientifically coherent entities.

The cyclical nature of the modeling process is also stressed by the framework for modeling competence (FMC; Chap. 1), according to which the phenomenon (i.e., the experiential world) is distinct from the model (i.e., the model world). However, the two worlds are interconnected. In the framework, the identification of the phenomenon under study is followed by the data collection process, which leads to the construction of the first model. Likewise, the authors of the FMC propose that, at the experiential level, the modeler observes and investigates the phenomenon with the aim of constructing multiple models as part of the process of model development.

Simultaneously, the identified purpose of the model, which is influenced by the modeler's experiences, sets the basis for the construction of multiple models, also as part of the process of model development. In the MLF, each model prototype (Version 1, 2, 3, …n) passes through an evaluation and validation process, which is conducted on the basis of the three criteria (model representation, interpretation, and prediction). The FMC also acknowledges the connection between the various versions of the model and the experiential world. This is done through model testing aiming to verify conformity. It is implied through the MLF that by implementing the modeling-based learning cycle, a student-constructed model is continuously evaluated and improved through the practice of model revision. At the same time, students are aware of the fact that different model prototypes are constructed by different students in their class (or scientists in the field), which could lead to different models of the same phenomenon, often based on different ideas/hypotheses. This helps the teacher overcome the problem identified by Grünkorn, Upmeier zu Belzen, and Krüger (2014), who proposed that students encounter difficulty in accepting the existence of multiple models. These researchers suggested that users should avoid the reflective use of historical models in school because it might lead students to fail to accept the existence of multiple models.

A detailed description of the MLF is the focus of the next section. We propose that the MLF is a tool that can be used by science educators to structure instructional designs and assessment methods to support the development of the modeling competence.

3.2 A Framework for Modeling-Based Learning

We view modeling as a competence because this term is comprehensive enough to indicate that modeling entails more than just knowledge or skills, a claim that has been emphasized in the literature (e.g., Klieme, Hartig, & Rauch, 2008). For instance, in prior research, modeling has been conceptualized as (a) an ability or a skill, which consists of modeling sub-skills (Dori & Kaberman, 2012; Papaevripidou, Constantinou, & Zacharia, 2007), (b) a practice (National Research Council, 2012; Pluta, Chinn, & Duncan, 2011; Schwarz et al., 2009), (c) a scientific process (Crawford & Cullin, 2004; Sins, Savelsbergh, & van Joolingen, 2005), or (d) an instructional approach (Louca, Zacharia, & Constantinou, 2011). Our definition of modeling is related to Weinert's (2001) definition of competence, which refers to the successful mastery, through an appropriate understanding and practices, of a concise range of demands, tasks, problems, and goals that are related to some performance that is of interest to both the community and society. Additionally, as Weinert purports, competence draws on combinations of the cognitive, motivational, moral, and social underpinnings that are available to (or can potentially be learned by) a person or a community and that underlie the concise mastery in question. Consequently, the concept of competence designates a complex action system encompassing all types of knowledge, including cognitive skills, attitudes, and other non-cognitive components. Additionally, it involves the ability to meet complex demands by drawing on and mobilizing epistemological resources in a particular context (OECD, 2003; Rychen & Salganik, 2003). The MLF is primarily a structural construct that describes the constituent components that should be in place for a modeler to be competent. However, different teaching interventions suggest that a developmental layout for each of the components presented in Fig. 3.2 could be compared with the learning progression presented by Schwarz and her colleagues (Schwarz et al., 2009; Schwarz, Reiser, Acher, Kenyon, & Fortus, 2012).

Before describing the proposed MLF, it is important to point out that it differs from "model-based learning," which has been used extensively in prior research to denote learning with mental models (Clement, 2000; S. Gilbert, 1991; Gobert & Buckley, 2000). By contrast, the MLF concerns the active participation of learners in modeling-based learning instruction, which engages them in the construction, revision, refinement, and validation of external representations or artifacts that purport to meet the criteria necessary to ensure their classification as scientific models.

Efforts to design modeling-based learning instruction have relied on an understanding of modeling competence with constituent components in two broad categories, namely *modeling practices and modeling meta-knowledge* (Nicolaou, 2010; Papaevripidou, 2012; Papaevripidou, Nicolaou, & Constantinou, 2014; Fig. 3.2). Attempts to validate such designs have led to the claim that learners' modeling competence can emerge and evolve as a result of their active participation in modeling practices with the concurrent development of meta-knowledge about modeling. Model construction (Stratford, Krajcik, & Soloway, 1998), model use (NRC, 2012), model comparison (Penner, Giles, Lehrer, & Schauble, 1997), model revision (Wu, Krajcik, & Soloway, 2001), and model validation (Halloun, 1996) have been identified as the main *practices* that learners engage in, during modeling. Metacognitive knowledge about the modeling process, which refers to a learner's ability to

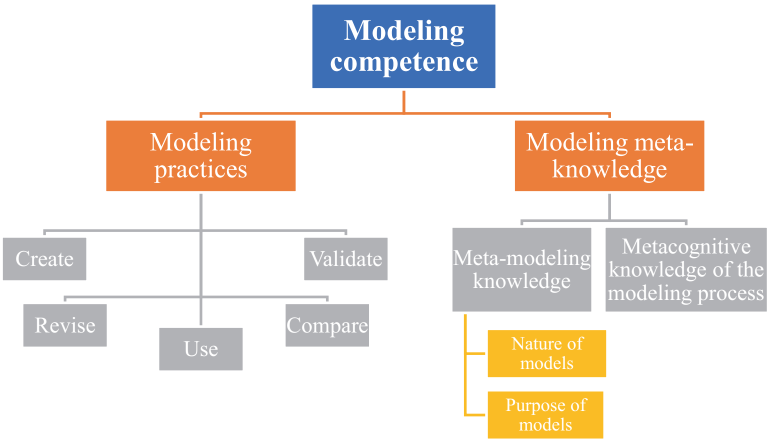


Fig. 3.2 Constituent components of the modeling-based learning framework (Nicolaou & Constantinou, 2014)

explicitly describe and reflect on the actual process of modeling, and meta-modeling knowledge (Schwarz & White, 2005) (i.e., an epistemological awareness of the nature and the purpose of models) together shape the meta-knowledge about modeling.

3.2.1 Modeling Practices

Model construction pertains to a learner's ability to develop an external representation of a physical phenomenon, a system, or an object (Constantinou, 1999; Namdar & Shen, 2015) after he or she has collected data by directly observing the phenomenon or indirectly by using secondary sources. In doing this, the learner needs to consider the modeling medium, his or her familiarity with it, the type of information that is available, and data on the phenomenon. A competent modeler is one who can construct a model that entails clear representational, interpretive, and predictive power.

First, a model with representational power includes objects, variables, and processes:

(a) Objects or entities constitute the core components of a model because they form the basis on which the rest of the components will be based (e.g., animals, plants, air, and water in a forest ecosystem, or the earth, sun, and moon in the solar system).
(b) Variables are the changing aspects characterizing the objects or the phenomenon as a whole (e.g., size, population, velocity).
(c) Processes are usually series of occurrences that produce change. In a model of how thermal equilibrium is attained, "heat flow" is a process, driven by the difference in temperature between two objects and causing change in the internal energy of the interacting objects.

Second, interpreting a phenomenon is about providing a story of how a phenomenon comes to manifest itself. For example, consider the following "story," which explains the mechanism by which the volume of a ball increases when it is heated: "The volume of a ball depends on the amplitude of the oscillation of its atoms. When a ball is heated, its temperature increases, and the kinetic energy of its atoms increases. The amplitude of their oscillations gets bigger. Therefore, the volume of the ball increases." An interpretation will typically include the relationships between the objects, variables, and processes. These interrelationships could be of a causal nature (e.g., the increase in the temperature of an iron cube causes an increase in its volume) or non-causal (e.g., an animal interacts with plants to eat them or with other animals of the same species to reproduce). The interpretive power of the model is related to its efficacy in providing one or more mechanisms that underlie the behavior of the phenomenon (Berland & Reiser, 2009; Braaten & Windschitl, 2011). Mechanisms are organized so that they produce regular changes when comparing the initial with the final conditions of the phenomenon under consideration

(Machamer, Darden, & Carver, 2000). Mechanisms tell us how the various processes and the interrelationships work together to manifest the observable aspects of the phenomenon.

Third, a model has predictive power when it allows the formulation and testing of predictions for new or future aspects of the phenomenon it represents (Bunge, 1983; Hughes, 1997). A model is an epistemological object that allows the user to change the input variables and record different outputs. Hence, a constructed model allows at least some of its elements to be changed and the resulting changes in the behavior of the phenomenon to be observed. This aspect of a model is of particular importance as predictions form a significant aspect of the usability of scientific models (Bunge, 1983) and also provide a clear means for testing and validating models.

Model use is a practice that is often closely connected with model construction. Like scientists and engineers, in the MLF, learners use the models they construct to express their current understanding of the system (or parts of the system). The purpose is to use the models to develop questions and interpretations and to communicate ideas to others (National Research Council, 2012; Nersessian, 2008). Learners who become competent in using models gain a purposeful, meaningful, and fruitful understanding of scientific knowledge (Xiang & Passmore, 2015) with respect to its content as well as its procedural and epistemological aspects.

Learners, like scientists and engineers, typically formulate various models of different forms. In order to make a decision about how and which of these prototype models to reject in favor of the most appropriate model that satisfies a set of specific criteria, learners need to be engaged in another practice: *model comparison* (Stratford et al., 1998). The importance of this modeling practice was delineated by Penner et al. (1997), who declared that "understanding the possibility of different models, and thinking about the advantages and disadvantages of various alternatives, might in turn support children's progress from a primarily descriptive use of models to a beginning recognition that models can serve as instantiations of rival hypotheses" (p.126). To practice model comparison, the learner should be capable of selecting the most appropriate model from among a series of models for the same hypothesis, and this model should be related to a phenomenon under study that satisfies certain criteria with respect to its representational, interpretive, and predictive power.

During modeling, the learner revisits the phenomenon under study and identifies the discrepancies that appear when comparing the phenomenon with the model that is being constructed. In doing so, the learner is engaged in the practice of *model revision* (Stratford et al., 1998; Wu et al., 2001). Model revision pertains to the learner's ability to (i) contrast a model with its corresponding phenomenon, (ii) evaluate it on the basis of the absence or presence of a model's basic components, and (iii) find ways to integrate missing parts or remove redundant parts in order to produce a revised model. Fretz et al. (2002) stated that the scientific practice of evaluating a model involves several actions, such as predicting what would happen, identifying anomalies, interpreting and critiquing the results, and proposing solutions. Similarly, Stratford et al. (1998) asserted that *testing and debugging* are examples of modeling activities that learners can productively engage in when testing the model, trying different possibilities, identifying problems with its behavior, and searching for solutions.

The constructed model is complete when it is also validated (often with other phenomena from the same class). *Model validation* refers to the learner's ability to abstract the model from the phenomenon and apply it in a new situation, possibly in phenomena of the same class. If the model fails to account for a new phenomenon, the learner needs to formulate a new model that will successfully describe, represent, and predict the observable patterns of both phenomena. Halloun (1996) asserted that "validation includes different forms of assessment that provide learners with opportunities to fulfill a major objective of science education: *critical thinking*" (p. 1028). To better describe this practice and differentiate it from model revision, consider an elastic collision of two balls (A, B) of equal mass (Ma = Mb), one moving at a constant horizontal velocity (Va) and one at rest (Vb = 0) (Fig. 3.3a). A modeler builds a "transfer model" (Ball A transfers its velocity to Ball B), which includes a mechanism for an exchange of velocity between the two balls. Then, a new phenomenon of the same class is presented (Fig. 3.3b). The "transfer" model is not consistent. Ball A does not transfer its velocity to Ball B. The model's validity is therefore tested. To account for the new phenomenon of the same class, the modeler constructs a "swap" model with a different mechanism that now pertains to the swapping of velocity during the collision. The validation process can continue with new phenomena (Fig. 3.3c) until the model validation process leads to the construction of the momentum model.

The validation of a model is an important part of the modeling process. It serves as a confirmation of viability or as an indication of room for improvement in the learner's model. However, it is often ignored during instruction. There is a need for improved scaffolds and more elaborate designs for teaching-learning sequences to facilitate the practice of model validation.

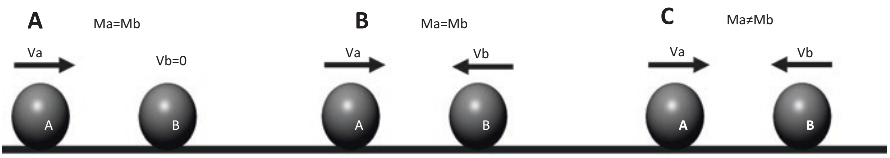


Fig. 3.3 Elastic collisions: Three phenomena from the same class. M stands for the masses of the two balls, V for their velocities. The three collisions could be modeled with three models of increasing sophistication and validity: velocity transfer, velocity swapping, momentum exchange. (**a**) moving ball colliding with stationary ball of equal mass; (**b**) balls of equal masses colliding with equal speeds in opposite directions; (**c**) collision between balls of different mass moving with different speeds in opposite directions

3.2.2 Modeling Meta-Knowledge

Learners engaging systematically with the five modeling practices will have mastered modeling competence to a great extent. However, there are other aspects of knowledge that are equally important to the successful modeler, namely, the modeling meta-knowledge (Schwarz & White, 2005, p. 167). With respect to modeling, meta-knowledge is shaped by metacognitive knowledge about the modeling process as well as meta-modeling knowledge.

Metacognitive knowledge about the modeling process refers to the ability of a learner to explicitly describe and reflect on the major actions undertaken to model a phenomenon under study (the modeling-based learning cycle; Fig. 3.1). For instance, one starts by observing the phenomenon that is of interest, collects information from the phenomenon, formulates a model by implementing the collected information, contrasts the formulated model with the phenomenon as a means of evaluating the model, revises the model in the light of new information that was not implemented in the original formulation, and then repeats the process in an iterative and cyclical manner with the purpose of refining the model to make it consistent, rigorous, and usable for testing hypotheses and making predictions.

The second aspect of meta-knowledge is "meta-modeling knowledge," which refers to developing an understanding of the nature of models and an appreciation of the purpose of scientific modeling. Engaging learners to simply develop models is not enough for developing an epistemological awareness of models and modeling. Deviating from Schwarz and White (2005),[2] the MLF distinguishes between metacognitive knowledge about the modeling process (which is metacognitive knowledge about how to construct and validate scientific models) and meta-modeling knowledge (which is epistemic knowledge about the *nature* and *purpose* of models in science). Consequently, *meta-modeling knowledge about the nature of models* entails a definition of models in terms of their *representational*, *interpretive*, and *predictive powers*. Likewise, *meta-modeling knowledge about the purpose and use of models* entails an epistemic understanding of the purposes of models in science. For instance, models (i) serve as sense-making tools for constructing knowledge, (ii) are used as communication platforms for conveying understanding or knowledge, (iii) can be used to develop new understandings by predicting new aspects of phenomena or showcasing mechanisms, and (iv) are used to illustrate, interpret, and predict phenomena (Schwarz et al., 2009).

[2] These researchers propose that meta-modeling knowledge consists of (i) the *nature of models*, (ii) the *nature or process of modeing*, (iii) the *evaluation of models*, and (iv) the *purpose or utility of models*.

3.2.3 The Role of Reflection and Metacognition in Modeling-Based Learning

The relationship between the epistemological underpinnings of modeling and actual modeling practices has been investigated in only a few studies (Cheng & Lin, 2015; Gobert et al., 2011), even though it has been emphasized as an important goal of science education (National Research Council, 2012, 2013; Nicolaou & Constantinou, 2014).

The MLF presents a conceptualization of what scientists do with modeling as well as what science educators expect learners to do with modeling. Therefore, for someone to be competent in modeling, he or she needs to be able to practise modeling as well as to exhibit meta-modeling knowledge and metacognitive knowledge about the modeling process. Stated differently, both the practical aspect (modeling practices) and the epistemological aspect (meta-knowledge) of modeling are important to a competent modeler.

For scientists who engage in authentic inquiry as established members of a scientific community, it is not necessarily sufficient in and of itself to ensure informed epistemological conceptions or conceptions that are identical to the conceptions of other members of the scientific community (Constantinou & Papadouris, 2012). Those who engage in authentic scientific inquiry might or might not develop epistemological views that are aligned with philosophically informed perspectives on scientific practice (Papadouris & Constantinou, 2014). Those views may be bound to the context of the individual scientist, and individual contexts may vary considerably across and within scientific disciplines (Schwartz & Lederman, 2008).

Educational research findings have demonstrated that for learners to develop the epistemological bases of scientific knowledge, implicit instruction is not sufficient. There is a need for explicit epistemological discourse that places features of the epistemology of science at the center of instruction and is both taught and assessed (Schwartz, Lederman, & Abd-El-Khalick, 2012). In the same line of reasoning are findings from studies by Gobert et al. (2011) who investigated the effects of modeling activities performed by students in three subject areas (Physics, Biology, and Chemistry) and found no significant relationship between students' understanding of models and their modeling practices in biology and physics. This was not the case for Chemistry, where a weak but statistically significant relationship was identified. In Chemistry lessons, students were explicitly taught about the nature and purpose of models, whereas in Physics and Biology, no support for the teaching of the nature of models and modeling was implemented.

In the same vein, Cheng and Lin (2015) conducted a study to explore the relationship between students' views of scientific models and their ability to generate their own models. Their study shed light on the relationship between students' model construction practices and their epistemological views on models and modeling. More specifically, they found that a few students who had shown above-average science learning performance and interest in science were able to develop coherent microscopic models. By contrast, students with lower science learning performance and interest were only able to develop observational or fragmented models. With regard to the relationship between students' views of the nature of models and their self-developed models, these researchers found that students who could develop coherent microscopic models had a better understanding of some aspects of the epistemology of models (i.e., representations of models, models as explanatory tools, and the use of scientific models) than students who had developed models at the observational level. Nevertheless, this study did not find any statistical evidence that the sub-factors of "models as exact replicas" and the "changing nature of models" were associated with the development of students' modeling competence.

Finally, the FMC (Chap. 1) suggests that this competence is the ability to reflect on models and modeling but leaves the role of practicing modeling somewhat unclear, perhaps implying that a competent modeler is the one reflecting correctly and successfully on the process of modeling and the nature and purpose of models regardless of his or her ability to really construct, use, compare, revise, and validate models (Krell et al., 2012).

On the basis of the conflicting discourse presented in this chapter on the connection of modeling practices, the epistemology of models, and the theoretical underpinnings of modeling competence, we propose that:

(a) A modeler who is competent in modeling practices is not necessarily an epistemologically competent modeler (Cheng & Lin, 2015; Gobert et al., 2011; Guisasola, Almudí, & Zubimendi, 2004).
(b) An epistemologically competent modeler is more likely to be competent in modeling practices (Sandoval, 2015; Schwartz & Lederman, 2008).
(c) An epistemologically incompetent modeler, however, is not necessarily incompetent in modeling practices.

Taken together, these three claims support the existence of the dual nature of the MLF and the need to develop both instruction and assessment that will support both modeling practices and the modeling of meta-knowledge. Additional research is needed to further clarify the interconnectedness between the reflection aspects of the MLF and using it in practice.

3.3 Monitoring the Development of the Modeling-Based Learning Framework

Several assessment tasks have been designed to be consistent with the MLF, and they were used to assess learners' modeling competence in various domains and in different instructional situations. These formative and summative techniques were employed in the framework of a series of teaching interventions (Papaevripidou et al., 2014) and through the use of a variety of data collection tools (Nicolaou, 2010; Nicolaou & Constantinou, 2014; Papaevripidou, 2012). This perspective enabled us to examine learners' modeling competence in a comprehensive manner and to arrive at a holistic view of how it emerges. Specifically, the designed interventions, which followed modeling-centered scientific inquiry principles, differed with respect to (a) the content of the curriculum, (b) the age of the participants, and (c) the modeling tool used by learners. However, they maintained the same format and duration, with each intervention lasting for about 8–10 90-min sessions.

At the beginning and end of each intervention, each component of the MLF was evaluated through a set of two assessment tasks. The two assessment tasks had the same structure (e.g., they consisted of a scenario and open-ended questions). Both the scenarios and the questions were comprised of short and simple statements. The assessment tasks were grouped in such a way that each modeling competence component was evaluated by two tests in two different subject areas (e.g., Test 1: free fall and Test 2: evaporation). The purpose of designing and administering two tasks for each of the components of the MLF was to explore whether modeling competence is content-dependent or not (Papaevripidou et al., 2014).

Students' responses to each diagnostic test were subjected to phenomenographic analysis, which led to the construction of different attainment levels for each component of modeling competence. The results of phenomenography (Marton, 1981) are a set of logically interrelated category conceptions (in this case, comprising the modeling competence), which are usually created on the basis of their content and their correctness (scientific level) and are differentiated from each other on the basis of qualitative criteria (Nicolaou, 2010). Here, the categories qualitatively describe the different ways in which the participants responded to each component of modeling competence prior to and after the teaching intervention.

The analysis of the collected data (from the whole series of interventions and assessment tools) revealed different levels of increased sophistication that exist for each component of the MLF among learners. Figure 3.4 provides a summary of the most superior level that emerged for each component of the MLF. As such, it also serves as an illustration of how the content of the MLF was reframed on the basis of the most superior level that emerged from the analysis of the data collected during the interventions. It is notable that the most superior levels were most commonly found to emerge after learners participated in modeling-based instruction.

For each component of the MLF presented in Fig. 3.4, specific hierarchical levels with increased sophistication that illuminate the degree of development of learners' modeling practices and their modeling of meta-knowledge emerged. Figure 3.5 presents the hierarchical levels that emerged from the data analysis with regard to the practice of revising the model. The tests for evaluating model revision asked students to first observe a specific model (e.g., a diagram presenting the photosynthetic growth of a plant) and state whether the model was complete. If they considered the model to be complete, they were asked to describe the ways in which the model appeared to be complete. Otherwise, they were asked to state how they would improve the model.

Component	**Highest attainment level**
I. <u>Modeling practices</u>	
• *Model construction*	Construction of a model that (i) provides a *comprehensive representation* of the phenomenon (e.g., all types of the components of the phenomenon are represented), (ii) encompasses both a *mechanistic interpretation* of how the phenomenon functions and a *causal interpretation* that explains why the phenomenon functions the way it does, and (iii) has *strong predictive power*.
• *Model use*	Efficient use of a model to (a) describe a phenomenon, and/or (b) interpret how the phenomenon functions, and/or (c) predict its future behavior or state.
• *Model comparison*	Detection of the best or worst model based on the model's (i) *representational comprehensiveness,* (ii) *interpretive potential*, and (iii) *predictive power*.
• *Model revision*	Proposal of specific model revision measures after identifying the limitations of (i) the representational completeness of the model (e.g., absence of objects, variables, or processes among the components of the model), (ii) the interpretive potential of the model (e.g., the model is missing a mechanism that explains how the phenomenon functions), or (iii) the predictive power of the model.
• *Model validation*	Validation of the model on the basis of the comparison of the two phenomena with respect to the model's components (e.g., The two phenomena do not share the same variables, so the new data cannot be used with this model).
II. <u>Meta-knowledge</u>	
• *Metacognitive knowledge about the modeling process*	The process of modeling involves (i) collecting information about the phenomenon (e.g., performing observations and collecting data, identifying objects, variables, processes, and interactions), (ii) selecting the most appropriate means for building the model, (iii) building a model on the basis of the data that were collected, (iv) comparing the model and the phenomenon or the model with other models, (v) evaluating the model according to its representational completeness, interpretive potential, and predictive power, (vi) improving the model, (vii) testing the validity of the model, (viii) repeating steps (iv) through (vii).
• *Meta-modeling knowledge*	
- Nature of models	A model describes, represents, and explains a phenomenon under study (e.g., provides a possible mechanism for how the phenomenon functions) and can be used to test predictions about specific aspects of the phenomenon.
- Purpose of models	The models serve as (i) instructional aids, (ii) simulations, (iii) facilitators of the conceptual understanding of the phenomenon under study, (iv) communication tools, (v) external representations of a phenomenon under study, and (vi) vehicles for formulating and testing predictions.

Fig. 3.4 Summary of the highest levels of attainment in school for each of the MLF components

3.4 Conclusions and Discussion

The implementation of a framework that is grounded in contemporary perspectives of learning science through modeling has great potential for classroom use because it can promote significant aspects of modeling-centered inquiry teaching and learning. The MLF presents a conceptualization of what scientists do while modeling as well as what science educators expect learners to do when developing and using models. Based on the MLF, learners are expected to practise modeling (to construct, use, compare, revise, and validate models) but also to develop modeling meta-knowledge, that is, to explicitly describe and reflect on the actual process of modeling as well as to become epistemologically aware of the nature and the purpose of models.

Level and Description
Level 6*. The learner identifies the need for in-depth improvements with regard to the representational, interpretive, and predictive power of the model The model is not complete because (1) it does not provide a strong representation of the phenomenon. The learners identify deficiencies with respect to: (a) its objects (carbon dioxide, oxygen, starch, etc.), (b) its variables (intensity of light, humidity, air composition, etc.), (c) its processes (photosynthesis, transformation of carbon dioxide and water into glucose and oxygen, transport of water in the plant, etc.), and (d) its relations (relation between the quantities of carbon dioxide and oxygen, relations between light, chlorophyll, and the process of photosynthesis, etc.), (2) it does not fully interpret the phenomenon (it does not reveal how photosynthesis happens, how the plant takes in water and other resources, what factors are important, or what the processes are), (3) it does not have predictive power (What will happen if the humidity increases or if the sun is not present for some period?).
Level 5. The learner identifies the need for in-depth improvements with regard to two of the model's utilities Level 5.3. ….the interpretive and predictive power of the model. Level 5.2. ….the representational and predictive power of the model. Level 5.1. ….the representational and interpretive aspects of the model.
Level 4. The learner identifies the need for in-depth improvements with regard to one of the model's utilities Level 4.3. ….the model's representational power. Level 4.2. ….the model's interpretive power. Level 4.1. ….the model's predictive power.
Level 3. The learner identifies that the model needs superficial representational and interpretive improvements
Level 2. The learner identifies that the model needs superficial representational improvements
Level 1. The learner identifies that the model needs unspecified improvements (which may result from their personal experience or from focusing on the superficial features of the model)
Level 0. Irrelevant or no answer (The model is incomplete. No improvements are needed)

* Level six includes learners' responses that are closer to the scientifically correct perspective.

Fig. 3.5 Levels of attainment for the practice of model revision (using photosynthesis as an example)

When comparing the MLF to the FMC, specific differences arise. The latter describes the aspects of modeling competence (i.e., the nature of models, multiple models, purpose of models, testing models, changing models), and it provides a description of three different levels for each of these five aspects, which are based on whether the modeler considers a model to be a "model for something" or a "model of something" (Mahr, 2009; in Krell, Reinisch, & Krüger, 2015). At the first level of each aspect, the FMC describes modelers' beliefs with respect to models of something, whereas at the third level, the FMC states modelers' reflection with respect to the essence of models for something.

The MLF distinguishes between modeling practices and meta-knowledge (learners' reflection on models and modeling) and considers them both equally important for teaching and learning, whereas the FMC refers only to learners' cognitive reflections about models and modeling. Additionally, each of the five modeling practices is important and has its own levels of competence according to the MLF. For example, model construction is one of the five constituent components of the practices that need to be developed by a competent modeler and is at the same level of importance as the remaining four practices (use, compare, revise, validate). The levels of attainment for each modeling practice (Fig. 3.5) are based on (a) what students actually do while practicing modeling, that is, when developing models, and (b) how students reflect on their competence to do so. By contrast, the model construction practice is not referenced in the FMC. Moreover, the validation practice seems to be absent from this framework. These researchers acknowledge that the testing and modifying of models to resolve inconsistencies emerge when comparing the model to the phenomenon, but no reference is made to phenomena of the same class. However, this practice is also important to the development of modeling competence in accordance with research claims that challenging students to defend the validity of their models results in significant improvements in their scientific discourse (White & Frederiksen, 1990).

With respect to the modeling of meta-knowledge, the FMC entails the notion of metacognitive knowledge of the modeling process through the aspects of "testing models" by considering that at the second level, modelers are able to show the correspondence between the model and the initial object (i.e., test a model of something). Additionally, at Level III, modelers test the model of something by verifying hypotheses during the application of the model. Therefore, the notable difference between the two frameworks with respect to meta-knowledge is that the MLF considers the idea that a metacognitively competent modeler is the one who can reflect on the process that *the modeler him- or herself followed* when engaging with the five modeling practices (i.e., creating, using, comparing, revising, and validating) a model. It is therefore considered to be an externalization of the steps already followed by the modeler when constructing and revising a model.

The MLF considers practices and meta-knowledge to be equally important and necessary for the development and assessment of modeling competence. On the other hand, the FMC maintains a rather different view. It emphasizes a theoretical understanding of models and the reflection on the process of modeling and acknowledges modeling competence as an ability to reflect on models and modeling. This underlines the importance of gaining insightful knowledge with models, judging models with regard to their purpose, and reflecting on the process of gaining knowledge through models and modeling (Upmeier zu Belzen & Krüger, 2010). This emphasis on meta-modeling competence will affect the design of teaching interventions as well as assessment efforts to evaluate modeling competence. Following the principles of the FMC, when developing modeling-based learning and teaching interventions, the focus should be (only) on developing learners' meta-modeling competence, and hence, the actual extent of "hands-on" modeling could be underestimated. Additionally, it is implied that an assessment of a learner's meta-knowledge is sufficient to help the assessor understand whether the learner is a competent modeler or not.

The presented MLF can be used to track the development of learners' modeling competence. The levels of increased sophistication that emerged for every component of the MLF (Fig. 3.5) provide a useful guide that instructors can use to better understand students' progress and even predict many of the difficulties that might emerge when implementing modeling-based learning. It can also assist in the design and organization of learning experiences and assessment tools that recognize and take advantage of the most likely trajectories that are typically followed by students as they move toward expertise (learning progressions; Schwarz et al., 2009, 2012). Because textbooks rarely include modeling assignments that invite students to actively practice modeling (van der Valk, van Driel, & de Vos, 2007; VanLehn, 2013), the clarification of each constituent component of the MLF can inform science educators and curriculum designers how to design and teach learning sequences for modeling and also additional assessment tasks to evaluate students' modeling competence in unison.

The need for a coherent framework that can help define what is being assessed as well as the subdimensions of modeling has been suggested before (Nicolaou & Constantinou, 2014). In previous work, modeling competence was not defined or assessed in a unified manner. Each study presented by this review paper has defined and assessed only one part of what can be conceptualized as modeling competence on the basis of available theoretical frameworks (National Research Council, 2012; Penner et al., 1997; Schwarz et al., 2009; Stratford et al., 1998). Even in cases where one aspect of modeling was under investigation, researchers have often used different definitions and consequently different assessment approaches. The MLF serves as a means for overcoming the fragmented diversity identified by Nicolaou and Constantinou (2014). The unifying nature of the MLF with respect to the complementary and interconnected relationship between modeling practices and the modeling of meta-knowledge as a combination of the nature/role of models and the modeling process is the most powerful characteristic of this framework. As such, the framework can serve as a basis for conceptualizing the teaching and assessment of modeling competence in a holistic manner, in contrast to focusing, as most published research has done, on one part of the modeling meta-knowledge (i.e., meta-modeling knowledge). Metacognitive knowledge about the modeling process is equally important for a robust development of the modeling competence. Additionally, this meta-knowledge should not be examined in isolation from modeling practices because being a competent modeler is not based exclusively on learners' modeling meta-knowledge or on learners' modeling practices. On the contrary, it is based on a learner's ability to both practise modeling and to demonstrate an understanding of the modeling process and the nature of models as epistemological entities.

Further research is needed to investigate and clarify the role of reflection and metacognition in modeling practices, both for scientists who work with models in their everyday activities and for learners who use and develop models in the framework of structured teaching interventions aimed at enhancing modeling competence.

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