Chapter 18
Attainments and Challenges for Research on Modeling Competence

Jan van Driel, Dirk Krüger, and Annette Upmeier zu Belzen

An understanding of the nature of models and model building is an integral component of science literacy.
S.W. Gilbert (1991, p. 78)

18.1 Introduction

Models rank among the main products of science, and models are constructed and applied in research in all scientific disciplines (Gilbert, Boulter, & Elmer, 2000; Gilbert & Justi, 2016; Harrison & Treagust, 2000). If we want students to "learn science in a way that reflects how science actually works" (NRC, 1996, p. 214), the role of models and modeling should be central in science education, from the early years into higher education.

To develop students' modeling competence, we need to distinguish between the major overarching goals of science education. Hodson (2014) argued that these include:

- *Learning science*—acquiring and developing conceptual and theoretical knowledge.
- *Learning about science*—developing an understanding of the characteristics of scientific inquiry, the role and status of the knowledge it generates (…)

J. van Driel (✉)
Department of Education, Melbourne University, Melbourne, Australia
e-mail: j.vandriel@unimelb.edu.au

D. Krüger
Department of Biology, Biology Education, Freie Universität Berlin, Berlin, Germany

A. Upmeier zu Belzen
Department of Biology, Biology Education, Humboldt-Universität zu Berlin, Berlin, Germany
e-mail: jannette.upmeier@biologie.hu-berlin.de

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- *Doing science*—engaging in and developing expertise in scientific inquiry and problem-solving. (Hodson, 2014, p. 2537)

Referring to Chap. 1, in which the idea for the book is tied in with previous research, and the terms model and modeling are defined on the basis of a literature review, we discuss how these goals are related to modeling competence. Related to *learning science*, we emphasize the medial function of models in imparting and acquiring knowledge. We explain that models are themselves products of science activity and thus tools for teaching and reflecting on the nature of the natural sciences (*learning about science*). Finally, we argue that, related to *doing science,* it is important that students are engaged in the process of modeling: constructing and testing their own models, or applying and reconstructing existing models, to develop skills on the basis of authentic modeling experiences.

To achieve these goals, it is important that teachers, textbook authors, science education researchers, and curriculum developers are aware of how models are actually developed and used by present-day scientists in their research endeavors. However, textbooks for secondary science education often present models as static facts or as final versions of scientific knowledge. The possible limitations of a model or the way in which a particular model was developed are seldom addressed. Moreover, textbooks rarely include modeling assignments that engage students in actively constructing or testing models (Erduran, 2001). Research on teacher knowledge in the domain of models and modeling in science has indicated that many science teachers have limited knowledge about the nature of models and the act of modeling (e.g., Borrmann, Reinhardt, Krell, & Krüger, 2014; Krell & Krüger, 2016; Van Driel & Verloop, 2002).

The present book provides an overview of recent international research on the teaching and learning of models and modeling in science, with a focus on modeling competence. The different sections of the book address the abovementioned issues. Section A focuses on the nature of models and modeling in science and how teaching and learning in this domain can be aligned with authentic scientific practices. Section B describes five studies on ways to assess modeling competence, while teachers' knowledge and strategies are central in Section C. Finally, Section D presents the findings of five studies on the development of students' modeling competence. This final chapter reviews the major contributions of this book to the research-based literature on models and modeling in science education and addresses some of the challenges and implications for further research and development.

18.2 Attainments: What Have We Learned?

Central in this volume is the framework for modeling competence (FMC), which is introduced and explained in Chap. 1. Competences have been defined in various ways in the literature. In this volume, we have adopted the view that competences include knowledge and skills that manifest themselves during performance.

Competences are not personal qualities but are learnable, and their development is related to specific domains and contexts. The FMC includes five aspects, each of which can be performed at three levels of increasing (theoretical) sophistication. Only level III meets all the abovementioned goals because, at this level, models are seen and used as research tools, whereas levels I and II focus on the medial role of models. In subsequent chapters, authors have referred to this framework, used it, or applied it, and some have suggested amendments or further refinements.

On the basis of a philosophical analysis, Aduriz-Bravo (Chap. 2) concluded that the FMC implies that school science would be analogous to scientists' science and that it allows students to work in ways that mirror those of scientists. Schwartz (Chap. 4) related modeling competence to the nature of science (NOS), demonstrating that one cannot be seen in isolation of the other: Understanding how scientists generate and develop knowledge requires insights into the epistemic nature of models and modeling. In other words, an understanding of NOS is implied in the FMC, although it is not explicitly stated. The author argued that a "requisite for understanding NOS and exhibiting level III of modeling competence involves acknowledging that a scientific model is not an exact replica of reality but a representation that serves to explain features and relationships that the scientists find curious and significant with respect to their questions" (p. 19). The chapter concluded with implications for the design of education, enabling science learning that closely reflects "how science actually works." The authentic practices of scientists were France's (Chap. 5) focus, whereby she described two detailed cases that demonstrate how models and modeling are front and center in these practices. The author argued that students' modeling competence will benefit from experiencing the messiness, creativity, and complexity of authentic modeling processes. These chapters are consistent with the framework proposed by Van der Valk, Van Driel, and De Vos (2007), which consists of a set of common features of models as recognized by practicing scientists. The framework of these authors focuses on the nature, purpose, and functions of models and recognizes the role of creativity.

Some of the subsequent chapters focused on ways to assess the modeling competence of both students and teachers or others. Taken together, these chapters demonstrate the need to develop multi-method approaches to capture the abovementioned complexity of modeling practices. In combination with verbal data (e.g., collected through interviews, think-aloud protocols), visual data can provide insights into what gets noticed during the act of modeling. Ubben, Salisbury, and Daniel (Chap. 6) described the affordances of eye-tracking technology in the context of assessing and researching modeling competence. Mathesius and Krell (Chap. 7) reviewed more traditional, "closed-ended" writing tasks that are used to assess the understanding of models and modeling in science, concluding that most existing instruments fail to capture the multidimensional nature of modeling competence in a valid manner. Applying the FMC, Schouten, Van Joolingen, and Leenaars (Chap. 8) studied the effects of drawing-based modeling, supported by a digital tool, on students' modeling competence. They reported that, although students' gains were limited, the models and reasoning logs created by students provided valuable insight into students' development of modeling competence and are thus appropriate instruments for assessing students' modeling competence.

Crawford and Flanagan (Chap. 10) focused on teachers' modeling competence in the context of the broader goal of developing scientific literacy among their students. They concluded that programs for teacher learning are needed to provide sustained and meaningful experiences concerning all aspects of models and modeling. Such programs contribute to the development of teachers' modeling competence, which, in turn, will serve to foster their students' critical thinking skills and scientific literacy. In the next chapter (Chap. 11), Ke and Schwarz illustrated how teachers can be supported to meaningfully engage their students in modeling and, by addressing epistemic considerations, scaffold them in developing their modeling competence. Crucially, the authors argued, teachers need to understand and enact productive interactions with their students. Campbell, McKenna, An, and Rodiguez (Chap. 12) also focused on meaningful student-teacher interactions. These authors explored how teachers might use "redirection" (Lineback, 2015) as a responsive methodological construct in an MLF environment. The authors demonstrated that when appropriate curricular and pedagogical frameworks are connected, a consistent focus on modeling can help a teacher place students' ideas in the foreground, scrutinize students' ideas, and use different forms of responsive instruction. As a result of this, students' modeling competence might flourish.

Other chapters described promising strategies for developing students' modeling competence. Krell and Hergert (Chap. 9), for instance, showed how an instructional sequence involving a black box could facilitate modeling practices. The approach encourages students to make their modeling activities explicit, thus fostering their meta-modeling knowledge. Louca and Zacharia (Chap. 14) used the FMC as a reference for capturing the development of the modeling competence of elementary school students who participated in a modeling-based learning environment. The authors drew attention to the role of the teacher who might use the FMC as a guide for pushing students' thinking in a particular direction. Thus, the FMC can provide teachers with a productive tool for scaffolding students to reach level III of the aspects of the framework. Similarly, Forbes and Schubert-Lange (Chap. 15) discussed the FMC as a tool that teachers can use to capture, assess, and support elementary school students' modeling competence. They described a study that laid the foundation for continuing collaborative research, aimed at supporting 3rd grade students' modeling competence in a particular domain (i.e., water systems). One of their conclusions was that if teachers are going to create supportive learning environments to foster students' modeling competence, they cannot actually make this happen unless they are prepared and supported. Bielik, Stephens, Damelin, and Krajcik (Chap. 16) focused on system modeling competence. The authors reported on an online computational modeling tool that can support students' modeling practices and systems thinking in the context of a high school chemistry unit. They proposed a framework of four key aspects of system modeling competence that is consistent with the FMC and extends this by incorporating the notion of systems thinking.

18.3 Challenges: Proposed Adaptations or Extensions of the FMC

The FMC was hypothesized as an initial competence model in the field of models and modeling. In accordance with Koeppen, Hartig, Klieme, and Leutner (2008), it refers to the cognitive facet of competence, whereas motivational components are not included. The FMC is conceptualized as comprising the abilities needed to engage in modeling practices (*Doing science,* see above) as well as knowledge of models (*Learning science)* and the modeling process in science (*Learning about science)*. Although the FMC does not refer *explicitly* to meta-modeling knowledge (Schwarz & White, 2005), the focus on the understanding of models and modeling processes is meant in the sense of meta-modeling knowledge (cf. Krell & Krüger, 2017). This was recognized by Constantinou, Nicolaou, and Papaevripidou (Chap. 3) who described the modeling-based learning framework (MLF). These authors argued that modeling competence includes the abilities to practice modeling and demonstrate meta-modeling knowledge, "which refers to developing an understanding of the nature of models and an appreciation of the purpose of scientific modeling" (p. 8) in addition to having metacognitive knowledge about the modeling process.

Building on their prior work, Ke and Schwarz (Chap. 11) used the Epistemologies-in-Practices (EIP) framework, which focuses on the nature and purpose of models. Comparing this framework with the FMC, the authors noted that both frameworks share a focus on using models as sense-making tools to explain and predict phenomena. However, they concluded that the two frameworks have different perspectives: While the EIP framework is situated in specific modeling settings and practices, "the FMC points to individuals' general understanding about models (e.g., nature of models and multiple models) and the process of modeling (e.g., testing and changing models) assuming they can be applied to different modeling contexts" (p. 19). This idea is consistent with the view that the FMC is content-free (Chap. 1). Ke and Schwarz (Chap. 11) explicitly used the term *explain* as a scientific activity in their EIP framework. By contrast, in the FMC, the term *explain* (level II) can be generally understood as a pedagogical as well as a research activity (Rocksén, 2016). On level II, explaining is used in a pedagogical sense, and it refers to making something understandable for somebody, for example, by describing or clarifying known relationships and correlations between the variables that are part of the phenomenon under investigation. In a scientific context, however, scientific explanations are put forth to answer three questions: What do we know? Why does it happen? How do we know? (Rocksén, 2016). First, if the term *explain* is used in a biological context, explanation refers to a proximate causation, which explicates a biological function in terms of physiological or environmental influences. In this case, explaining is related to how something happens. Second, an explanation ultimately refers to a cause, which explicates traits in terms of evolution. In this case, explaining is related to how something happened. Because these two scientific meanings of explanation share hypothetical components, they would be located on level III of the FMC.

Lehrer and Schauble (Chap. 13) have worked with elementary students for many years, inventing, testing, and revising models as important mechanisms that can support learning in ways that are largely consistent with the FMC. However, these authors prefer the term "representational competence" to describe their goals for young children. They see the relationship between representations and models as a fluid continuum, aiming to expand representational competence "toward more elaborated forms of modeling that acknowledge multiple models of the phenomena under investigation" (p. 24).

Capps and Shemwell (Chap. 17) focused on the notion of thinking of models as abstractions. They proposed a modification to the FMC such that thinking about models as abstractions is recognized as a key element under the aspect of the "nature of models" and is given a more prominent position in the framework. They argued that the term abstraction reflects the most fundamental characteristic of models, that is, "they are representations that pull structure away from that of their referents" (p. 11). Therefore, they explained that they prefer the term abstraction over the terminology in the FMC. The same authors also challenged the two upper levels of the aspect of the "nature of models" in the FMC, that is, idealized representations (level II) and theoretical reconstructions (level III), arguing that it is unclear whether these levels "lie along a single dimension of measurement. To explain, while 'idealized representations' is clearly ontological, 'theoretical constructions' seems to incorporate the epistemological idea that models are conjectural. In the suggested formulation, this epistemological component would be shifted to another dimension of the framework" (p. 12). However, level III entails epistemological perspectives across all aspects of the FMC.

18.4 Ideas for Future Research

This book focuses on a competence-based approach to models and modeling in science education, the underlying approach referring to competence models, which are prominent in German-speaking countries (Blömeke, Gustafsson, & Shavelson, 2015; Klieme, Hartig, & Rauch, 2008; Chap. 1). However, alternative approaches are well established (e.g., Chaps. 3 and 14), for example, based on the notion of learning progressions, which is prevalent in the United States (Lehrer & Schauble, 2015; Schwarz, Reiser, Achér, Kenyon, & Fortus, 2012; Chaps. 4 and 11) or the use of rubrics (Andrade, 2000; Burke, 2006). Rubrics entail indicators of a given competence in terms of descriptions of different states. While the competence-based approach was initially grounded in theory, learning progressions for scientific modeling (e.g., Schwarz et al., 2009) are also based on empirical findings on student thinking and learning. This leads to the question of which conceptual aspects of such models might be similar or different. The fact that different approaches have been developed under different conditions such as cultural backgrounds, national curricula, and standards as well as different school systems shows the need for international discussions.

Upmeier zu Belzen, Alonzo, Krell, and Krüger (2019) started working to address parts of this question by comparing learning progressions and competence models in the field of models and modeling by applying the criteria: kinds of models, model structure, application to teaching and learning, and evaluation through research. The authors concluded that differences in the origins and original purposes led to different emphases in research efforts. Learning progressions are grounded in empirical findings on student thinking and learning and have resulted in strong hypotheses on how to foster students' modeling competence. Competence models, often structured into aspects and levels, are theoretically grounded; and evaluation efforts tend to focus on the empirical investigation of the structure of the model. However, in order to reflect on the purposes of such research, it might be helpful to think about what researchers working with these different approaches can learn from each other.

As several options for the assessment of competences are executed in this book, we are able to describe student performance at single time points with regard to special aspects of theoretical models by descriptive data. To date, these studies have focused on demonstrating that each cell of the FMC describes a distinct separable part of students' modeling competence (Krell, Upmeier zu Belzen, & Krüger, 2016). But still, Mathesius and Krell (Chap. 7) concluded that, "clearly more research is necessary to develop and evaluate scales and questionnaires for the assessment of the different aspects of modeling competence" (p. 14). Future research should therefore focus on the development and use of instruments that are designed for assessing modeling competence, for example, in large-scale longitudinal studies and for diagnosing individual student learning (Gogolin & Krüger, 2018). In addition, causal explanations for the observations of students' modeling competence are still lacking, and thus, we recommend controlled experimental studies with pre- and post-tests on the conditions of competence development. This could be done with different assessment methods, also including assessments of performance (Shavelson, 2013). Performance-based assessment might also be a relevant source of evidence for validating performed competences.

In the context of assessment efforts, validation becomes more and more important in terms of the interpretation of test scores with regard to theory. To date, objectivity and reliability are considered in most studies using assessment instruments (Chap. 7), but different sources of validity evidence have not been investigated as much: test content, response processes, internal structure, relations-to-other-variables, and consequences of testing (AERA, APA, & NCME, 2014).

Constantinou, Nicolaou, and Papaevripidou (Chap. 3) contended that in the MLF, modeling practices and meta-knowledge are equally important, "while the FMC refers only to learners' cognitive reflections about models and modeling" (p. 13). They concluded that further research is needed to investigate and clarify the role of reflection and metacognition in modeling practices, in both the contexts of scientific work and science learning. Similarly, Krell and Hergert (Chap. 9) questioned the relationship between meta-modeling knowledge and modeling processes. The authors challenged the common assumption of a positive relationship, that is, that meta-modeling knowledge guides the practice of modeling (e.g. Schwarz et al., 2009), and they argued that future research is needed to provide empirical evidence to support or reject this assumption.

Based on approaches from a specialist perspective, the classification of models and modeling processes from a student perspective should also be investigated (Krell, Upmeier zu Belzen, & Krüger, 2014a; Meisert, 2008). This should avoid the development of plain ontological categories (cf. Ritchey, 2012) and include the classification of modeling processes besides the classification of models themselves (e.g. modeling pedagogies: Campbell et al., 2015; Campbell et al., 2013).

There are repeated indications that what students think about models and modeling depends on the respective model (Krell, 2013; Krell, Upmeier zu Belzen, & Krüger, 2014b) and the relevant discipline (e.g., biology, chemistry, or physics; Krell & Krüger, 2017; Krell, Reinisch, & Krüger, 2015). It is necessary to examine the extent to which the specific context can be systematically measured as a "difficulty-generating task characteristic" (Hartig & Frey, 2012; Prenzel, Häußler, Rost, & Senkbeil, 2002) and how this influences the completion of the tasks (Krell et al., 2014b). It is necessary to clarify how specialized knowledge, the knowledge of certain models, and the meta-knowledge of models are related to problems. Related to this, Forbes and Schubert-Lange (Chap. 15) called for future research to investigate the impact of students' modeling competence on their reasoning about familiar and unfamiliar scientific concepts. In conclusion, we recommend that future research focus on students' use of scientific models across different content domains and types of models as well as within different modeling practices and epistemic considerations.

Several chapters (i.e., Chaps. 11, 12, 14, and 15) demonstrated how the FMC can provide teachers with a tool for capturing and supporting their students' modeling competence. These chapters concluded that teachers need to be prepared and supported in order to be able to create supportive learning environments that actually foster students' modeling competence. Specifically, this requires teachers to understand and enact meaningful interactions with their students (Chaps. 11 and 12). Specific learning resources and programs are needed to assist teachers in developing this expertise. Research is necessary to investigate the efficacy of such programs. Ke and Schwarz (Chap. 11) concluded that there is still a lot "to be learned about how to meaningfully engage students in scientific modeling and how to support teachers in doing so. Understanding the interactions of teaching and learning along with supporting teachers to enact these productive interactions will be critical to advancing the field" (p. 24).

18.5 Conclusion

This book opened with a statement about the increased recognition of models and modeling as a core practice of scientific work and, consequently, of the importance of engaging students in an authentic modeling practice as a key element of their science education. The research presented in this book spanned a wide range in terms of theoretical and methodological perspectives as well as the contexts and settings of the authors. Despite this variety, there seemed to be a consensus about the idea that, ranging from students' early years to the university level, if science education in the twenty-first century aims to provide students with up-to-date scientific experiences, a central role should be played by learning scientific models, learning to model, and learning about models and modeling. This book brings together a number of approaches and perspectives that are geared toward providing such learning opportunities and reports on research evidence for the effectiveness of some of these approaches. The FMC, as shown in this book, can play a prominent role in this context. It can be used to design curriculum materials and teaching-learning sequences for students as well as (pre-service) teachers. In addition, it can be used as an analytical framework for the assessment of students' modeling competence and teachers at a particular time or to monitor the development of these competences over time. As became apparent in this book, the FMC can be used productively alongside other perspectives and approaches. Through its use in a variety of contexts, the FMC itself is in need of further development. Suggestions for future research that can inform this development include instruments and procedures for assessing modeling competence, the relationships between meta-modeling and meta-cognitive knowledge and modeling practices, and longitudinal research on the development of students' modeling competence over time.

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