Chapter 4
Modeling Competence in the Light of Nature of Science

Renee S. Schwartz

4.1 Introduction

> *All scientists use models, and if they say they do not, then they are failing to understand what they are doing.* (Aquatic ecologist)

Competence is described as "domain-specific cognitive dispositions that are required to successfully cope with certain situations or tasks, and that are acquired by learning processes" (Koeppen, Hartig, Kleime, & Leutner, 2008, p. 62). With respect to a biological context specifically, Upmeier zu Belzen and Krüger (2010) state that modeling competence includes (1) the ability to get purposeful new insights into biological topics with models, (2) the ability to judge on models and the process of modeling in relation to the purpose, (3) the ability to reflect upon the process of getting insights with models, (4) the motivational and social willingness to use these abilities in problem based situations.

By these descriptions, then, a competence-based view of models in science can be considered a contextually-based cognitive function needed to understand a scientific concept or scientific process. In other words, modeling competence in science involves the epistemic practices of knowledge generation through the understanding and use of scientific models. Scientists rely on modeling competence to gain an understanding of nature and natural phenomena. As expressed in the introductory quote above, if a scientist says they do not use models, they do not understand what they are doing (or, perhaps, they are not doing science). The epistemic functions of scientific models have been described as "a bridge between scientific theory and the world-as-experienced ('reality')" (Gilbert, 2004, p. 116). Gilbert drew from the

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literature to describe several depictions of models and model use within science, including abstractions of theory, idealized reality, visible or simplified phenomena/abstractions, and explanations that enable predictions. These descriptions have been further elaborated and extended in more recent writings (e.g. Gilbert & Justi, 2016). Moreover, various frameworks for how learners' understand models and modeling have been discussed and refined (i.e. Grünkorn, Upmeier zu Belzen, & Krüger, 2014; Krell, Upmeier zu Belzen, & Krüger, 2014; Mahr, 2011). A synthesis of this work yielded the competence-based view on models and modeling.

Understanding what science is and what scientists do requires epistemic knowledge, which includes the nature of science [NOS]. Scientists generate scientific knowledge through practices that are uniquely scientific, grounded in empirical observations of the natural world. Because models and modeling are both practices and products of science, modeling competence necessitates an understanding of NOS and the practices of scientific inquiry. This chapter explores these connections and their place within science education. To gain additional perspective on a competence-based view of models and representations of NOS in authentic contexts, this chapter also examines how practicing scientists describe the role of models and modeling in their research. This perspective provides insights into the meaning of the opening quote, as well as how modeling competence reflects the epistemic nature of science and scientific practices.

4.2 Theoretical Background

4.2.1 Nature of Science: A Cognitive Construct

The phrase "nature of scientific knowledge" [NOS] refers to characteristics of scientific knowledge inherently derived from the manner in which that knowledge is produced through scientific practices (Lederman & Lederman, 2014). These qualities, or characteristics, are what make scientific knowledge *science*, as opposed to other forms of knowledge. The specifics of NOS have been described in various ways; all delineating scientific knowledge as foundational to how we can understand the natural world through empirical observation. With respect to what is relevant and appropriate for science teaching and learning, there is broad consensus within the literature that strongly supports the view that NOS is a *cognitive* construct (Lederman & Lederman, 2014; Osborne, Collins, Ratcliffe, Millar, & Duschl, 2003; Schwartz, Lederman, & Abd-El-Khalick, 2012) rather than a skill, attitude, or activity. Others have provided more general descriptions of science through emphasis on broader epistemic and philosophical commonalities across knowledge domains, such as "features of science" (Matthews, 2012) and "family resemblance" (Dagher & Erduran, 2016; Irzik & Nola, 2014).

Despite the debates, there is a developmentally appropriate level of generality regarding NOS that is accessible to pre-university students and relevant to their daily lives. These general, cross-cutting characteristics representing the nature of scientific knowledge as a cognitive outcome are described here (modified from Schwartz, Lederman, & Crawford, 2004; Schwartz, Lederman, & Abd-El-Khalick, 2015). Figure 4.1 provides a description of each of the aspects that hold consistent agreement amongst science educators.

These aspects are not a definitive or privileged listing of NOS, but rather a compilation of aspects commonly advocated within empirical research dating back to the 1960s. These aspects are considered cross-cutting because regardless of the science domain, one can find representative examples (McComas, 2008; Schwartz & Lederman, 2008). Furthermore, these aspects should be considered *a collection*, as opposed to isolated features. Understanding NOS includes understanding how these aspects are intricately connected and derived from the scientific enterprise. For example, due to the inherent subjective and socio-cultural features of scientific knowledge, that knowledge is inherently tentative, yet robust due to the empirical foundation upon which the knowledge is generated.

NOS has been advocated for scientific literacy for decades (Lederman & Lederman, 2014). Driver, Leach, Millar, and Scott (1996) argued that scientific literacy comprises understanding scientific inquiry; understanding the social nature of science; understanding that people produce, validate, consume, and benefit from scientific knowledge; and understanding some aspects of science content. Each of these can be connected to why understanding NOS is relevant, as scientific knowledge is developed through inquiry practices, in a social context, by real people, and leads to further understanding of the natural world. Because many natural concepts are complex and not directly observable; and because relationships among components of natural phenomena are not always directly accessible, models and modeling are essential to inquiry practices and the generation of scientific knowledge. Thus, as detailed in the theoretical Section A of this book, understanding and being able to utilize models for learning and decision-making; or, in other words, engaging in and understanding modeling competence is essential to scientific literacy.

4.2.2 *Scientific Models and Modeling in Science Education*

To promote epistemological views of science, learners should experience science through engaging in scientific practices (AAAS, 1993; Lead States, 2013; NRC, 1996, 2000, 2012).

> Inquiry is a critical component of a science program at all grade levels and in every domain of science, and designers of curricula and programs must be sure that the approach to content, as well as the teaching and assessment strategies, reflect the acquisition of scientific understanding through inquiry. Students then will learn science in a way that reflects how science actually works. (NRC, 1996, p. 214)

NOS aspect	Description
Empirically-based	Scientific knowledge, including scientific models, is based on and/or derived from observations of the natural world. These observations are made directly or indirectly through use of senses, tools, measuring devices, and other technological instruments that offer detection of natural phenomena.
Distinction between observation and inference	Observations are descriptive statements about natural phenomena that are directly or indirectly (through instruments) accessible to the senses. Inferences serve to explain or extend observations but are not directly accessed. The notion of gravity is inferential in the sense that it can only be accessed and/or measured through its manifestations or effects. Models, as theoretical constructs, are based on observations and provide inferential explanations of relationships and functionality.
Creativity	Science, as a human endeavor, involves the invention of explanations, negotiation of meaning from data, and the generation of ideas. This aspect of science, coupled with its inferential nature, entails that scientific concepts are functional theoretical models rather than faithful copies of reality. For example, the observation of birds in flight inspired studies of aerodynamics and the eventual invention of flight mechanisms.
Distinction between scientific theories and laws	There is an epistemic distinction between scientific theories and laws, stemming from the type of evidence and functional purpose of the knowledge. Laws are descriptions of relationships among features of observable phenomena. Theories, by contrast, are inferred explanations for observable phenomena. Put simply, laws are statements of what is observed; theories are statements of why something occurs. For the example of gravitational force, Newton's law of gravity states that there is an attraction between two masses. Gravitational theory attempts to explain why this occurs. Models can depict relationships (such as in mathematical terms) and present theoretical constructs that explain interactions and functionality.
Subjectivity/theory-driven	Scientists' beliefs, previous knowledge, training, experiences, and expectations, in addition to theoretical commitments affect what problems scientists investigate, how they conduct their investigations, what they observe (and do not observe), and how they make sense of, or interpret observations. An evolutionary developmental biologist and an ecologist will interpret components of an ecosystem differently based on the lenses through which they work. Multiple models arise due to varying perspectives and purposes. The models scientists use to explain and test the system are necessarily informed by different theoretical lenses.
Socially and culturally situated	Science as a human enterprise is practiced in the context of a larger culture. Scientists are the product of that culture. Scientific knowledge affects and is affected by the various elements and intellectual spheres of the culture in which it is embedded. These elements include, but are not limited to, social fabric, power structures, politics, socioeconomic factors, philosophy, and religion. Related to the subjective and creative NOS, social and cultural influences are unavoidable. They reflect what questions are asked, how science is practiced, and what knowledge is generated and accepted. Through the ages, scientific models have reflected cultural and social positions (i.e. geocentric model), with society being resistant to changes that require profound paradigm shifts that run counter to societal and religious convictions (i.e. heliocentric model).
Inherently tentative	Scientific knowledge is necessarily subject to change, yet due to the empirical nature, scientific knowledge is also robust (not likely to change on a whim or without substantial evidence). Attaining absolute truth is outside the realm of science (Chalmers, 1982; Kuhn, 1962). Scientific claims change as new evidence is brought to bear on existing theories or laws, or as old evidence is reinterpreted in the light of new theoretical advances. A look through the history of science provides myriad examples of change in how we understand the natural world. Model revision can result from falsifying hypotheses through predicting and testing.

Fig. 4.1 Nature of science aspects and descriptions

4.2.3 Nature and Purpose of Scientific Models

Scientific models are integral to the development and exploration of scientific knowledge (e.g. Gilbert, 1991; Khine & Saleh, 2011; Mahr, 2011). Models have been described in a variety of ways, and in several chapters of the present book (Sec. A). Consistent among them is that models are representations that serve to describe, explain, or predict (Grünkorn et al., 2014; Schwarz et al., 2009; Van Der Valk, Van Driel, & De Vos, 2007; van Driel & Verloop, 2002). Gilbert (2004) describes models as "simplified depictions of a reality-as-observed, produced for specific purposes, to which the abstractions of theory are then applied" (p. 116), "idealizations of a possible reality" (p. 116), visualizations of abstract phenomena or of something too small or too big to see otherwise, simplifications of something complex, and "the basis for both scientific explanations of and predictions about phenomena" (p. 116). Models can represent myriad of phenomena including: objects, abstractions, systems, parts of systems, entities, relationships among entities, an event, a behavior, and a process (Gilbert, 2004; Mahr, 2011). Further, models are products of investigations, frameworks for investigations, and tools for predictions and testing (Gouvea & Passmore, 2017; Krell et al., 2014; Upmeier zu Belzen & Krüger, 2010; Van Der Valk et al., 2007).

Ontologically, models can be mathematical, physical, analogical, or mental constructs (representations) of the natural world (*what are models of?) (*Gouveu & Passmore, 2017; Mahr, 2011, among others). Models also have epistemic purposes (*what are models for?)* including that models: (1) explain or organize observations that then enable prediction and testing through further observation; (2) simplify a complex phenomenon or render an abstract concept visible; and (3) provide a framework for guiding further investigation. A model-object *of* an object (Mahr, 2011) is not an exact replica of the actual phenomenon or process; but serves as a representation of the model of the phenomenon (target, or object) and features deemed important and applicable to the structure and function of the target (object). Models are epistemic tools for explaining, predicting, visualizing, simplifying, testing, and showing relationships in the development of scientific knowledge.

4.2.4 Scientific Models in Science Standards

In the United States, the prominence of models and modeling competence in science education has increased in recent years with the inclusion of models within the essential scientific practices that learners should understand and be able to perform (Lead States, 2013). The scientific and engineering practices in the Next Generation Science Standards [NGSS] explicitly list "*Developing and using models*" among them. However, one can stress that developing and using models are integral to other scientific practices as well. For example, models and the modeling process are useful tools for conducting investigations (model a stream system to study impacts of erosion), analyzing and interpreting data (using a model of inheritance patterns to interpret generational data related to a genetically-based disease), and communicating information (demonstrating impacts of climate change).

To represent this idea further, the Framework for K12 Science Education (NRC, 2012), upon which the NGSS is based, discusses the importance of developing scientific proficiencies through engaging in the practices and epistemic thinking that generates scientific knowledge, including the role of models as products and modeling as practices within science. The Framework states, “Students’ opportunities to immerse themselves in these practices and to explore why they are central to science and engineering are critical to appreciating the skill of the expert and the nature of his or her enterprise” (NRC, 2012, p. 47). Clearly, in order to achieve this goal, learners must have a meaningful understanding of models and modeling as well as how these concepts relate to targeted features of NOS. The dynamic nature of scientific practices and the role of theories and models in the actions are parallel with the framework for the modeling process (Fig. 1.2). The competences associated with models and modeling are evident within the figure. Scientific practices embrace the role of models as epistemic tools used to formulate hypotheses, test and propose solutions, as well as generate arguments through analysis and evaluation of data.

The nature of scientific knowledge, including models, is also emphasized on an international level. The 2015 PISA Assessment and Analytical Framework (OECD, 2017) includes the nature and purpose of scientific models as part of their recommendations. The three competencies for scientific literacy are that learners should be able to (1) explain phenomena scientifically, (2) evaluate and design scientific enquiry, and (3) interpret data and evidence scientifically. The PISA Framework states that these “… competencies, however, require more than a knowledge of what is known; they depend on an understanding of how scientific knowledge is established and the degree of confidence with which it is held” (OECD, 2017, p. 21). They also state that the competencies require epistemic knowledge: “Epistemic knowledge includes an understanding of the function that questions, observations, theories, hypotheses, models, and arguments play in science” (p. 21).

Despite being targeted as an essential learning outcome for decades, students (Grosslight, Unger, Jay & Smith, 1991; Krell, Upmeier zu Belzen, & Krüger 2012), preservice teachers (Schwartz & Skjold, 2012, Hartmann, Upmeier zu Belzen, Krüger, & Pant 2015) and practicing teachers (Crawford & Cullen, 2004; Justi & Gilbert, 2003; van Driel & Verloop, 2002; Krell & Krüger 2015), typically hold narrow or varying conceptions of models. Yet, with scaffolding and experience, learners can develop understandings of scientific models and modeling (e.g. Akerson, White, Colak, & Pongsanon, 2011; Gilbert & Justi, 2016; Schwarz et al., 2009; Windschitl & Thompson, 2006). For example, Schwarz and colleagues used a model-centered, meta-modeling approach to engage learners in modeling activities as well as develop learners’ epistemologies of science (Schwarz & White, 2005). They attest to the effectiveness of the “meta” component when engaged with models and modeling as essential for fostering epistemic knowledge.

If children are to learn science in a way that reflects how science really works, it is important for teachers to have an understanding of these real workings of science and instructional strategies that are effective in developing modeling competence and epistemological views of science. Other chapters in Section A dive more deeply into the meaning and nature of scientific models and modeling, as well as the research on teachers' and learners' conceptions (Sec. C; Sec. D).

4.2.5 What Scientists Say About Models and Modeling in the Scientific Community

To get a sense of how models are defined and used in the scientific community, as products and practices of science, and then how models and modeling reflect NOS features, we can explore how scientists think about and use models in their own research (Chap. 5). Van Der Valk et al. (2007) conducted a study to test and revise a comprehensive description of "features of scientific models." Their study asked practicing scientists who had recently published research involving scientific models, to comment on the extent of their agreement or disagreement with the features. The study provides an empirically supported description of features of scientific models that represented views of contemporary scientists. In similar form, Schwartz (2004) conducted a study of scientists' views of NOS and scientific models. The following section presents partial results from this study, as they relate to how scientists' conceive the purpose of models. These descriptions reveal scientists' thinking about a competence-based view of models in their work. For the purpose of this chapter, the discussion draws clear connections between model descriptions and the aforementioned NOS aspects.

The current study reports on scientists' views of the purpose of scientific models and their use in authentic science practice. This study provides descriptions and examples of models and connections to NOS aspects. Results of a larger study on scientists' views of NOS have been reported elsewhere (Schwartz & Lederman, 2008; Schwartz, 2011). Participants were experienced scientists from four science disciplines (life science, earth science, physics, and chemistry) and who employed various approaches to research (e.g. experimental; descriptive; theoretical). The research question focused on here is "What are practicing scientists' views on the purpose of scientific models?" and "Do views vary based on science discipline and/or investigative approach?"

4.3 Method

Participants were 24 practicing scientists (6 female, 18 male) from across the United States and representing four primary science disciplines and a variety of sub-disciplines and investigative approaches (ten life scientists; five earth and space scientists, five physicists (four theoretical), four chemists). All of the participants were currently engaged in research and publishing. With an average of 25 years research experience since earning their doctorate, the participants were clearly experienced within their respective communities. With the exception of one participant (an aquatic ecologist with 22 years post PhD research experience, currently in a non-academic institution), all held tenured academic positions at universities. All were educated and currently employed within the United States. Most had extended international experiences through post-docs, sabbaticals, or collaborative programs.

4.3.1 Data Collection and Analysis

For the larger study, participants responded to two open-ended surveys [VNOS-Sci and VOSI-Sci] (Lederman et al., 2002; Schwartz, Lederman, & Lederman, 2008). These were modified to prompt the scientists to consider the NOS and inquiry aspects within the context of their research. Two questions were added to the VNOS-Sci survey that directly addressed ideas about the purpose of scientific models:

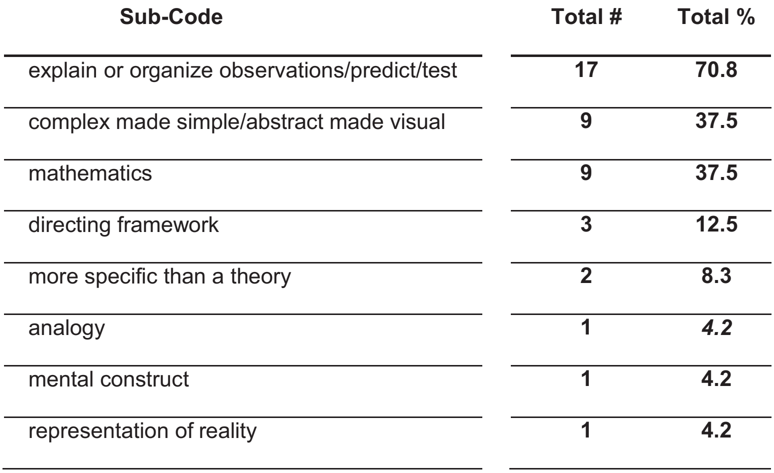
(a) What is the purpose of a scientific model?
(b) Describe a scientific model from your own area of research, if appropriate. If you do not use scientific models, describe a scientific model from another area of research. Describe why your example is a scientific model.

Semi-structured interviews served to elicit additional information as well as validate scientists' responses to questionnaire items (Lederman et al., 2002).

Through a process of analytic induction, participants' questionnaires and interviews were analyzed separately to generate individual profiles of scientists' views. Analysis specifically sought reference to models and model use. All instances of the words "models" or "use models" or similar phrases were coded. The sub-codes that emerged are descriptors of how the scientists talked about models (their own words), model construction, and model use. Each participant could have provided statements consistent with multiple sub-codes. Thus, results are presented as number of participants and % of participants who made reference to each sub-code. Results are reported based on emergent descriptions, trends, and patterns.

4.4 Results

The following results represent how the scientists describe models within their field (Fig. 4.2). The top descriptors are listed, with representative quotes to provide context and elaboration of meaning. It is important to note that the descriptors are what emerged from the voices of the scientists. They were not asked if they agree/disagree with a particular descriptor. Thus, the results are considered



Sub-Code	Total #	Total %
explain or organize observations/predict/test	**17**	**70.8**
complex made simple/abstract made visual	**9**	**37.5**
mathematics	**9**	**37.5**
directing framework	**3**	**12.5**
more specific than a theory	**2**	**8.3**
analogy	**1**	***4.2***
mental construct	**1**	**4.2**
representation of reality	**1**	**4.2**

Fig. 4.2 Scientists' descriptions of the purpose of models ($N = 24$)

"first ideas" of models that occurred to scientists as they provided their responses. Whether they agree or not with other descriptors is beyond the scope of this study. The sub-codes are not mutually exclusive. Many of the representative quotes included here fall within in multiple sub-codes. These results are discussed in terms of suggested patterns within this sample of scientists and should not be generalized beyond this sample.

4.4.1 Model Descriptions and Nature of Science Connections

The most common emergent themes are consistent with published descriptions of scientific models (Gilbert, 2004; Gilbert & Justi, 2016; Khine & Saleh, 2011; Van Der Valk et al., 2007). Moreover, the emergent themes are also consistent with many of the features of the modeling cycle (Fig. 1.2). Here, the scientists recognized the role of observation, testing, and influences. These results also reflect the aspects related to modeling competence. The findings described here are based on the emergent themes. Representative quotes are provided in nearly full form in order to provide voice to the scientists, which enriches the meaning through context and stories. Following the quotes, NOS connections are presented in *italics*. Where evident, connections to aspects and levels of the framework for modeling competence (Chap. 1) are made.

Explain or Organize Observations/Predict/Test Seventeen of the 24 scientists indicated models were explanations or ways to organize observations that also involved testing predictions (*purpose of models*: level III; Chap. 1). Most responses specifically related to the participant's research.

> In my research I use the model of a trophic cascade that indicates how predator-prey interactions from the top of the food web propagate down the food web to affect lower trophic levels. This model explains some of the variability observed in food web dynamics and the relative abundance of predator and prey groups in ecosystems. [aquatic ecology] [*subjectivity/theory-driven*]

> A scientific model is a description of a physical system that provides an understanding of what the system is and how it works. A scientific model allows us to organize our information about a system and to predict how the system might evolve or react… We use mathematical models of stellar atmospheres to compute what the spectrum of a star ought to look like. We compare the predicted stellar spectrum with the observed stellar spectrum to determine the composition of the star. [astronomy] [*subjectivity/theory-driven*]

An atmospheric scientist described the purpose of a model to provide understanding and predictability. In this way, he recognized the model function to be a tool to gain knowledge.

> As models become more complex, such as general circulation models of the atmosphere and ocean, the models are used as predictive tools. They're used to predict how climate will change as we change the composition of the atmosphere. [atmospheric science2]

The other atmospheric scientist expanded on this perspective by discussing modeling of a system. In this remark, the subjective/theory-driven nature of scientific models is clearly connected to *multiple models* (Chap. 1).

> You are probably aware that the treatment of clouds in climate models is one of the weakest links in the chain of things that we need to put together to say something sensible about global warming, and we don't do it very well. The models are all over the map, depending on how they parameterize the cloud process. [Atmospheric science1] [*subjectivity/theory-driven*]

Several responses within this sub-code demonstrated a connection between the scientists' views of models and their views of certainty of scientific knowledge (tentative NOS). These descriptions also related to the empirical NOS.

> It [a model] is a mental or physical construct. [...] The model is a way to test whether we got our ideas right [...] Then you can test it and try a different set of conditions. If they do, then it means the model is working, at least for these conditions, and it has some predictive function. One is to test the input to see if I have my ideas straight and the other is to make predictions. [Models are] useful to guide experimentation and serve as a provisional understanding of a phenomenon. [environmental analytical chemistry] [*empirical & tentative NOS*]

One of the biologists elaborated on her view of models and modeling within her field. With respect to modeling competence, her response demonstrates level III for a set of aspects: *purpose of models*, *multiple models* and *changing models* (Chap. 1).

> The theory of natural selection is also a model that explains much about the origin and behavior of biological systems. It provides a basis for making predictions about species responses to environmental changes … A lot of these conclusions are drawn from tests with models that show that if you create this kind of structure it accounts for the behavior that you measure. Again, just because you can come up with a model that explains it doesn't necessarily mean that is the only model. Just maybe we haven't thought of the model that works better … Models work at all these levels [hypothesis, theory, law]. A hypothesis is a model. The model becomes more robust as it becomes elevated to theory and then law. But a model initially is a hypothesis. [entomology] [*empirical & tentative NOS; theory & law* misconception]

This last statement shows a connection to the NOS aspect of “theory and law.” However, the scientist held a hierarchical view of hypothesis, theory, and law; yet also saw a connection with scientific models at each “level” of scientific knowledge. According to this scientist, the more robust the model, the higher its status within the perceived hierarchy. In contrast to other scientists who described models as having predictive capabilities based on assigned parameters (and these parameters could change according to what the intent is), the position described above may suggest a view that models can approach certainty. Even though different scientists held differing views of certainty of models, they held the common view of models having predictive ability (*purpose of models*: level III, Chap. 1). This feature of models exemplifies the subjective and theory-driven NOS because they describe models as providing an explanation or system upon which to base further exploration. Moreover, these descriptions also provide links to the empirical and tentative NOS, as the models must be based on natural phenomena, yet they can be adjusted with further testing.

In response to a prompt to discuss the development of the atomic model, one chemist explained the historical development of the atomic model, along with the explanatory and predictive power of this model across disciplines. In this response, we see a connection of atomic models to the *empirical, tentative, subjective, and creative NOS***.**

> Once the planetary model became acceptable, things that could be predicted from this model were consistent with what physicists were observing then it was quickly discovered that it was also consistent with the chemists, this whole body of knowledge that chemists were building. All of a sudden, the world was falling in place. Chemists could see very neatly how their atoms stuck together and begin to explain things. Linus Pauling came along and used the model, extended the model, to explain the chemical bond and all of modern chemistry … Of course over the years the model continues to be used and refined in ways we hadn’t even imagined. We are comfortable with that until some day we bump up against something we can’t explain with the model. At that time, we go back and try to adjust the model or come up with other explanations. It’s progressive. [mass spectrometry]

Complex Made Simple/Abstract Made Visual Nine participants describe models more specifically as a means to simplify a complex process or system or a means to visualize an abstract concept. Most representatives from within this sub-code were distinct from the previous in that rather than considering models as explanations of observations that serve a predictive function; models here are considered limited, but useful, explanations because they serve to simplify natural phenomena that would otherwise be too complicated to investigate further. These views aligned with levels II and III of *nature of models* (Chap. 1). The descriptions exemplify the subjective/theory-driven NOS because they indicate choices made by the scientists in determining what features of the real phenomena to include in the models. These choices are based on what the scientists consider to be important for answering their questions of interest.

> A scientific model helps to explain a natural situation. Often it is a small scale general version of a more complex phenomenon. Scientific models help us to grasp a complex situation as a more watered-down version. In the field of landscape ecology, scientists often cut fields into different patch sizes and patterns and study animal movements in them to model (simulate) how larger animals move about in larger more complex landscapes. Models can be increased in scope and complexity to further explain the variability we often encounter in nature. [wildlife ecology] [*subjective/theory-driven & tentative NOS*]

> The models are okay as long as you understand the limitations of them. That isn't really how it is but it's the way we think about it… . We are showing pictures here that relate to certain aspects of an atom. That is what you do when you see an elephant. It depends where you are looking on the elephant and what scale. [high energy theoretical physics] [*subjective/theory-driven, creative, tentative NOS*]

Mathematics Nine participants referred to models as mathematical representations. Within this sub-code were statements to demonstrate the role of mathematics in dealing with complexity. Interestingly, the theoretical physicists had a higher tendency to explain models as mathematical entities. They described situations where as the complexity of the phenomenon increases, capabilities of mathematics become more important.

> So for particle physics there is a theory now known as quantum chromo dynamics, QCD. It is a field theory […] To solve that problem requires exchange of 16 different particles simultaneously. So it requires hundreds of equations to be solved simultaneously, and they are integral equations. That has taken years of computer time for most elementary, even models there, how to solve that. But in theory one has a complete mathematical description. In practice you say let's model it by limiting the number of particles. That makes it a model. [computational physics] [*theory-driven, tentative, socio-cultural NOS]*

Directing Framework Even though the majority of descriptions and examples provided by the scientists eluded to connections to the subjective/theory-driven NOS, a few scientists explicitly made reference to models as a theoretical framework that guides their work.

> Without models, observation would amount to cataloging data … There is a lot of data, and it doesn't mean anything until you have a model. If you have all these data and lots of satellites taking all these data ... it doesn't tell you what to look for. It just tells you whether a model you have is plausible or not. It is all indirect. [astrophysics].

> A gene network is a scientific model, postulating patterns of interacting among gene products following an analogy with a computer wiring diagram. It illustrates a mechanism, and helps develop hypotheses about other genes that must be involved to produce the observed phenotype. [evolutionary development].

4.4.2 *Model Development, Model Use, and Nature of Science*

The scientists in this sample discussed models in terms of development and use. The epistemic nature and functions of models are exemplified in their responses. Model development is described as the process of collecting information (empirical and/or theoretical), identifying relationships, and composing an explanation of the relationships. All but the theoretical physicists suggested the proposed relationships should lead to predictions that are empirically testable. Because of their reliance on mathematical models and complex computations, the theorists' ideas push the boundaries of how we might define "*empirical* observations." This is also a societal or cultural issue in that technological advances have enabled scientists to enter the realm of virtual reality to develop, test, and use their models. Van der Valk et al. (2007) also described the role of technological advances related to model development and use. The notion of "empirical" is changing as our perspectives of what is possible changes. In this way, NOS is like any other scientific concept – subject to change.

Model use, and thus modeling competence, involves testing predictions and identifying problems or cases where existing models do not work. The tentative yet empirical nature of model development and testing, among other aspects, are articulated within this description from one of the atmospheric scientists who works with cloud climate models:

> Most of my work is testing models. Model development is a whole other field. That might be the theoretical side. So I put myself in the observational side as opposed to the theoretical side. The models themselves are so complex. How do you build them in the first place? So what do they do to build these models? ... Real clouds don't behave this way. … it is easy to suspect these models. Doing the realistic calculations is very difficult. It takes a lot of number crunching and time. But we can test these ideas. … if we know what we are doing there should be no difference between the model and our observation of the clouds…. They don't [work]. Even the bumps on the tops of clouds are enough to throw it off…. *When we build these models and test them, we play games like this.* We try to develop a test where we know what we should expect. We predict the results and see whether we get them or not. We see the failure of the prediction and start probing and say" how come?" [*empirical, tentative, subjective/theory-laden, creative*].

This example also depicts competence within all five aspects at level III (Chap. 1).

4.4.3 *Models and Anomalies*

This quote raises the practices of predicting and testing, much like many of the other quotes have. Yet, here we go a step further to see what happens when predictions do not play out as expected. The idea of "playing games" to get the best fit with real data is rarely examined in science education. However, understanding how anomalous data are recognized and dealt with is a feature of the scientific enterprise (Chalmers, 1982; Kuhn, 1996). In this study, scientists often connected use of models with identification of anomalies. The question of “how come?” offered by the atmospheric scientist above marks the curiosity and exploration into why a model doesn’t hold. From an epistemological perspective, this level of recognition would be essential for understanding the relationship between the empirical and tentative nature of science. For many of these scientists, it is in the testing of the models that anomalies are identified. Through exploration of anomalies, models are refined and/or new models are constructed.

The scientists indicated they would examine and attempt to explain an anomaly from the perspective of their existing framework (the subjective/theory-driven NOS). The cloud climate modeler quoted above fell within this category. In discussing competing models for the same anomaly, he described the need for better analysis and refinement of his model to explain the data. His statements also indicate a critical role of creativity and collaboration in how models can change:

> We are going to get better at our analysis of our data and when we do that it gets harder for people to say, “Ah ...” or how do you say, it motivates people to start looking at the model and ask what is really going on here. How do we understand this? Obviously, there is something strange going on here. By pursuing this and keeping the pressure up, I am hoping that people like John [colleague] will come along and start thinking again, “Well maybe if I did something else in *my* model … maybe we could pull this off.” [atmospheric scientist].

4.5 Discussion and Implications of What Scientists Say

Creating and using scientific models is central to scientific inquiry, and included as one of the eight scientific practices learners should be able to do and understand (Lead States, 2013). In the “What scientists say”-study, there was overwhelming sentiment that models are used to explain or organize observations, then predict and test through further observations. The emphasis here is on empirical observation in the development and in the testing of models. In comparison, half as many scientists described models as a means to visualize something abstract or simplify a complex process. This latter view seems to place less emphasis on direct observation and incorporates theoretical entities, although these are not necessarily mutually exclusive. These results show that these scientists’ perceptions and use of models fit broadly with published descriptions of functional roles of models in science, including descriptive, explanatory, and predictive characterizations (Justi & Gilbert, 2003, 2016; Van Der Valk et al., 2007; Van Driel & Verloop, 1999). The results demonstrate distinctions between *models of* and *models for* (Gouvea & Passmore, 2017). The multiple descriptors that the scientists used for models, such as mathematical, physical, and analogical, are also consistent with prior characterizations. In comparison to the range and multiple categories of meaning for the seven aspects of models identified in the Justi and Gilbert (2003) study of teachers’ views of models, the present study suggests these scientists may hold more consistent or similar views of scientific models, with prioritizing the epistemic function of predictive ability.

These results suggest that a competence-based view of models and modeling relies on understanding the explanatory and predictive nature of models. Definitions of "model" used by scientists have been suggested (Justi & Gilbert, 2003; Van Der Valk et al., 2007). The study by Van Der Valk et al. (2007) produced a set of "features of scientific models" and solicited input from scientists as to the relevance of the features to their work. The present study provides additional information from constructed response data which are useful, in conjunction with scientists' examples, to understand the modeling cycle as well as the modeling competence (Chap. 1). To further emphasize the relevance and importance of input from the scientific community, Chap. 5 of this volume presents additional research on scientists' descriptions of models and modeling. These examples, and the discussions provided in this book, partially fulfil the request from Bernd Mahr when he wrote, "Because models are the most important epistemic tool of our knowledge and production, it is necessary to produce a methodological surplus when answering the question, 'What is a model?'" (2011, p. 296).

4.6 Modeling Competence and Science Instruction: Engaging Authentically by Connecting Scientific Models and Nature of Science

What can we learn from scientists about a competence-based view of models and nature of science? We can learn how scientists develop and use models through authentic scientific practices. This chapter details relationships between NOS principles and modeling competence. For example, the utility of models within scientific research relates to their representation of phenomena or systems. System features are selected based on subjective decisions stemming from scientific questions under study. 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 to their questions. Models also enable prediction and testing; thus, progressing scientific understanding. Acts of model construction and utility are inherently inferential, creative, and tentative; yet robust due to the empirical basis, and explanatory and predictive power. For meaningful understanding of models and modeling, and to achieve a competence-based view of models, epistemic knowledge is also essential (Mahr, 2011). If one can "do" modeling, but does not understand the epistemic nature of what they are doing, have they really achieved meaningful understanding? Have they reached a competence-based view of models?

The different descriptions noted here suggest models are not a "one size fits all" concept. Not all models explain direct observations and not all models take an abstract concept and make it more concrete. What constitutes a model is determined by the scientist and scientific community. As Mahr (2011) stated, "It turns out that the phenomenon of model-being can be understood if one stops looking for an answer to the question *of the nature of a model* and starts asking instead *what justifies conceiving of something as a model*" (p. 253). Further, Mahr explains that epistemically, "the model-being of an object will become the result of a judgment which is situated in contexts of invention and justification, and whose acceptance and reasoning may thus be questioned" (p. 253). The examples provided by the scientists in the "What scientists say"-study reinforce the notion of development and use of an object as a model-being to be contextualized and somewhat idiosyncratically judged.

Similar to the findings of Van Der Valk et al. (2007), the scientists shed light on the empirical NOS and the changing landscape of how scientists work with changing technology. There is a need to reconsider and, perhaps, reconceptualise how we define "empirical" within the realm of scientific practices. Furthermore, model development is described as a practice distinct from model use. In order to help students "learn science in a way that reflects how science actually works" (NRC, 1996, pg. 214), teachers should incorporate a variety of experiences that demonstrate models and model use in an authentic light (Chap. 3). That is, for a competence-based view of models, both model development and model use need to be addressed in multiple contexts, with clear objectives that align students to distinctions and similarities among models with respect to the contexts, functions, and NOS connections. Teachers need to consider how the many model examples and modeling activities they provide for their students are opportunities to explicitly address NOS aspects (Crawford & Cullin, 2004). This type of model-based instruction with explicit/reflective attention to epistemic connections has been shown to be effective (e.g. Akerson et al., 2011; Gilbert & Justi, 2016; Schwarz et al., 2009; Windschitl & Thompson, 2006). The use of historical examples of models and modeling has been recommended for some time (Grünkorn et al., 2014; Justi & Gilbert, 2002; Chap. 3). The scientists' narratives here and in other chapters provide contemporary examples of types of models and modeling functions within the scientific community and how they represent important NOS features. These can be adjusted for use in science instruction.

Another intriguing connection of model use and NOS has to do with the identification and role of anomalies in science. Are they mistakes? Are they opportunities? A competence-based view of models must recognize the subjective and theory-driven NOS and include their functional influence on predicting and testing. When expectations are not met, what happens next? There is potential to *model* the practice of model testing, anomaly identification, and scientific progress. How are anomalies typically identified and dealt with in the classroom? Are models used to make predictions and test them? Are students given opportunity to experience the excitement of finding a contradiction between prediction and observation? Are students given opportunity to refine models or develop a new model in light of contradictions? These are questions that should be considered in instructional design so that science learning might more closely reflect "*how science actually works*."

References

Akerson, V., White, O., Colak, H., & Pongsanon, K. (2011). Relationships between elementary teachers' conceptions of scientific modeling and the nature of science. In M. Khine & I. Saleh (Eds.), *Models and modeling: Cognitive tools for scientific enquiry*. Cham, Switzerland: Springer.

American Association for the Advancement of Science. (1993). *Benchmarks for science literacy: A project 2061 report*. New York: Oxford University Press.

Chalmers, A. (1982). *What is this thing called science?* (2nd ed.). University of Queensland Press.

Crawford, B., & Cullin, M. (2004). Supporting prospective teachers' conceptions of modeling in science. *International Journal of Science Education, 26*(11), 1379–1401.

Dagher, Z., & Erduran, S. (2016). Reconceptualizing the nature of science for science education: Why does it matter? *Science & Education, 25*(1–2), 147–164.

Driver, R., Leach, J., Millar, R., & Scott, P. (1996). *Young people's images of science*. Buckingham, UK: Open University.

Gilbert, J. (1991). Model building and a definition of science. *Journal of Research in Science Teaching, 28*, 3–17.

Gilbert, J. (2004). Models and modeling: Routes to more authentic science education. *International Journal of Science and Mathematics Education, 2*, 115–130.

Gilbert, J., & Justi, R. (2016). *Modelling-based teaching in science education*. Cham, Switzerland: Springer.

Gouvea, J., & Passmore, C. (2017). Models of versus models for. *Science & Education, 26*(1–2), 49–63.

Grosslight, L., Unger, C., Jay, E., & Smith, C. (1991). Understanding models and their use in science: Conceptions of middle and high school students and experts. *Journal of Research in Science Teaching, 28*, 799–822.

Grünkorn, J., Upmeier zu Belzen, A., & Krüger, D. (2014). Assessing students' understandings of biological models and their use in science to evaluate a theoretical framework. *International Journal of Science Education, 36*, 1651–1684.33.

Hartmann, S., Upmeier zu Belzen, A., Krüger, D., & Pant, H. A. (2015). Scientific reasoning in higher education: Constructing and evaluating the criterion-related validity of an assessment of preservice science teachers' competencies. *Zeitschrift für Psychologie, 223*(1), 47–53.

Irzik, G., & Nola, R. (2014). New directions for nature of science research. In M. Matthews (Ed.), *International handbook of research in history, philosophy and science teaching* (pp. 999–1021). Dordrecht, the Netherlands: Springer.

Justi, R., & Gilbert, J. (2002). Modelling, teachers' views on the nature of modelling, and implications for the education of modellers. *International Journal of Science Education, 24*(4), 369–387.

Justi, R., & Gilbert, J. (2003). Teachers' views on the nature of models. *International Journal of Science Education, 25*(11), 1369–1386.

Khine, M., & Saleh, I. (Eds.). (2011). *Models and modeling: Cognitive tools for scientific enquiry*. Cham, Switzerland: Springer.

Koeppen, K., Hartig, J., Klieme, E., & Leutner, D. (2008). Current issues in competence modeling and assessment. *Zeitschrift für Psychologie/Journal of Psychology, 216*(2), 61–73.

Krell, M., & Krüger, D. (2015). Testing models: A key aspect to promote teaching activities related to models and modelling in biology lessons? *Journal of Biological Education*. https://doi.org/10.1080/00219266.2015.1028570T

Krell, M., Upmeier zu Belzen, A., & Krüger, D. (2012). Students' understanding of the purpose of models in different biological contexts. *International Journal of Biology Education, 2*, 1–34.

Krell, M., Upmeier Zu Belzen, A., & Krüger, D. (2014). Students' levels of understanding models and modelling in biology: Global or aspect-dependent? *Research in Science Education, 44*, 109–132.

Kuhn, T. (1996). *The structure of scientific revolutions* (3rd ed.). Chicago: University of Chicago Press.

Lead States. (2013). *The next generation science standards*. Washington, DC: The National Academies Press.

Lederman, N., & Lederman, J. (2014). Research on teaching and learning of nature of science. In N. Lederman & S. Abell (Eds.), *Handbook of research on science education* (Vol. II). Routledge: New York.

Lederman, N. G., Abd-El-Khalick, F., Bell, R. L., & Schwartz, R. S. (2002). Views of nature of science questionnaire (VNOS): Toward valid and meaningful assessment of learners' conceptions of nature of science. *Journal of Research in Science Teaching, 39*(6), 497–521.

Mahr, B. (2011). On the epistemology of models. *Rethinking Epistemology, 1*, 301–352.

Matthews, M. (2012). Changing the focus: From nature of science (NOS) to features of science (FOS). In M. S. Khine (Ed.), *Advances in nature of science research* (pp. 3–26). Dordrecht, the Netherlands: Springer.

McComas, W. (2008). Seeking historical examples to illustrate key aspects of the nature of science. *Science & Education, 17*(2–3), 249–263.

National Research Council. (1996). *National science education standards*. Washington, DC: National Academic Press.

National Research Council. (2000). *Inquiry and the National science education standards*. Washington, DC: National Academic Press.

National Research Council. (2012). *Framework for K12 science teaching*. Washington, DC: National Academic Press.

OECD. (2017). *PISA 2015 assessment and analytical framework: Science, reading, mathematic, financial literacy and collaborative problem solving*. OECD Publishing, Paris. https://doi.org/10.1787/9789264281820-en

Osborne, J., Ratcliffe, M., Collins, S., Millar, R., & Duschl, R. (2003). What "ideas about science" should be taught in school science? A Delphi study of the "expert" community. *Journal of Research in Science Teaching, 40*(7), 692–720.

Schwartz, R. S. (2004). *Epistemological views in authentic science practice: A cross-discipline comparison of scientists' views of nature of science and scientific inquiry.* Unpublished doctoral dissertation. Oregon State University, Corvallis, OR.

Schwartz, R. S. (2011). The nature of scientists' nature of science views. In M. S. Khine (Ed.), *Advances in the nature of science research: Concepts and methodologies* (pp. 153–188). Springer.

Schwartz, R., & Lederman, N. (2008). What scientists say: Scientists' views of nature of science and relation to science context. *International Journal of Science Education., 30*(6), 727–771.

Schwartz, R., Lederman, N., & Abd-El-Khalick, F. (2012). A series of misrepresentations: A response to Allchin's whole approach to assessing nature of science understandings. *Science Education, 96*(4), 685–692.

Schwartz, R., Lederman, N., & Abd-El-Khalick, F. (2015). Measurement of nature of science. In R. Gunstone (Ed.), *Encyclopedia of science education*. Dordrecht, the Netherlands/Heidelberg, Germany/New York/London: Springer.

Schwartz, R., & Skjold, B. (2012). Teaching about scientific models in a science content course. *Educacion Quimica, 23*(4), 451–457.

Schwartz, R. S., Lederman, N., & Lederman, J. (2008, April). *An instrument to assess views of scientific inquiry: The VOSI questionnaire.* Paper presented at the annual meeting of the National Association for Research in Science Teaching, Baltimore, MD.

Schwartz, R. S., Lederman, N. G., & Crawford, B. A. (2004). Developing views of nature of science in an authentic context: An explicit approach to bridging the gap between nature of science and scientific inquiry. *Science Education, 88*(4), 610–645.

Schwarz, C., Reiser, B., Davis, E., Kenyon, L., Acher, A., Fortus, D., et al. (2009). Developing a learning progression for scientific modeling: Making scientific modeling accessible and meaningful for learners. *Journal of Research in Science Teaching, 46*(6), 632–654.

Schwarz, C., & White, B. (2005). Metamodeling knowledge: Developing students' understanding of scientific modeling. *Cognition and Instruction, 23*(2), 165–205.

Upmeier zu Belzen, A., & Krüger, D. (2010). Modellkompetenz im Biologieunterricht [Modeling competence in biology education]. *Zeitschrift für Didaktik der Naturwissenschaften [Journal of Science Education], 16*, 41–57.

Van Der Valk, T., Van Driel, J., & De Vos, W. (2007). Common characteristics of models in present-day scientific practice. *Research in Science Education, 37*, 469–488.

Van Driel, J., & Verloop, N. (2002). Experienced teachers' knowledge of teaching and learning of models. *International Journal of Science Education, 24*(12), 1255–1272.

Van Driel, J. H., & Verloop, N. (1999). Teachers' knowledge of models and modeling in science. *International Journal of Science Education, 21*(11), 1141–1153.

Windschitl, M., & Thompson, J. (2006). Transcending simple forms of school science investigation: The impact of preservice instruction on teachers' understandings of model-based inquiry. *American Educational Research Journal, 43*(4), 783–835.