

A Review of Modeling Pedagogies: Pedagogical Functions, Discursive Acts, and Technology in Modeling Instruction

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The current review examined modeling literature in top science education journals to better understand the pedagogical functions of modeling instruction reported over the last decade. Additionally, the review sought to understand the extent to which different modeling pedagogies were employed, the discursive acts that were identified as important, and the technology leveraged in the pursuit of engaging students in developing and using models. After narrowing from 783 articles originally identified with an abstract keyword search, the literature review included a database of 81 research articles whose abstracts revealed a focus on modeling as an instructional intervention and contained learner modeling. A multistage process was then completed whereby each article was read and information from the articles were identified and discussed among a group of five researchers. The most salient findings identified in the research included (a) conceptual understanding was the most common pedagogical function identified for modeling, while developing facility and understanding of science practices was identified least often, (b) *Expressive modeling* was the most frequently used and sequences which connected *Exploratory* and *Experimental modeling* were the most frequently observed combination of modeling pedagogies, (c) the most important discursive acts identified as important were scientific reasoning, explanation, and peer-to-peer collaborative/cooperative learning, and (d) technology was used in approximately one-half of the research reviewed, with *Expressive* and *Exploratory* modeling pedagogies found most often supported or mediated by technology.

Keywords: Model, Scientific Model, Model-Based Learning, Model-Based Inquiry, Modeling Pedagogies

INTRODUCTION

Both scientists and engineers use . . . models—including sketches, diagrams, mathematical relationships, simulations, and physical models—to make predictions about the likely behavior of a system,

and they then collect data to evaluate the predictions and possibly revise the models as a result (NRC, 2012, p. 46).

This excerpt is taken from *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012) and emphasizes the central role models play in the enterprise of science and engineering. Increasingly, more science education researchers (Campbell, Oh, & Neilson, 2012; Kahn, 2011; Passmore, Stewart, & Cartier, 2009; Schwarz & Gwekwerere, 2007; Windschitl, Thompson, & Braaten, 2008) and U.S. national standards documents (NGSS Lead States 2013;

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State of the literature

- Science education researchers and standards documents have noted the importance of models in scientific activity and have called for an increased role for models in K-12 classroom versions of scientific activity.
- Five pedagogical conceptualizations for modeling, referred to as modeling pedagogies, have been proposed to align with how scientists use modeling in scientific activity.
- No comprehensive literature review exists examining the frequency and pedagogical purposes that technology has been used to support modeling instruction.

Contribution of this paper to the literature

- This research points to the importance of modeling instruction for developing students' conceptual understanding and understanding of the nature of models/science, while identifying a need for increased attention to how students' facility and understanding of science practices is understood as an outcome of modeling instruction.
- Visions, understandings, and mechanisms for engaging students in modeling pedagogies can be found in the literature to ground future research and provide mechanism for engaging students in modeling in classrooms.
- This research revealed the compatibility of technology and modeling and those types of modeling pedagogies that helped frame the role of technology within modeling contexts.

NRC, 2012) have noted the importance of models in science and engineering and have subsequently called for an increased role for models in K-12 science teaching and learning. As an example, Krajcik and Merritt (2012) argued, “[i]t is important for students to construct models that explain phenomena, show how their models are consistent with their evidence, and explain the limitations of those models” (p. 7). By engaging students in modeling through creating and revising models as explanations of phenomena, students not only gain abilities in the practice of modeling, they also gain understandings about the nature of models specifically, and the nature of science more broadly. This context positions students to experience sensible versions of the cognitive, social, and material work of scientists (Bell et al., 2012). But, because modeling has not been widely enacted as a pedagogy, it is conceptually-ill defined, like “inquiry” and “standards-based teaching” as examples of other broad and perhaps “elastically defined” approaches to science teaching

(Windschitl, Thompson, Braaten, & Stroupe, 2012). Consequently, little about the effectiveness of modeling pedagogies is known or few of the specifics of the pedagogical functions of modeling that can assist students in learning has been aggregated into a clear framework informed by important modeling research that has occurred. This literature review begins by intently focusing on the teacher to better understand the pedagogies that have been enacted and investigated, the pedagogical functions of these pedagogies, the critical discursive acts within these functions and pedagogies, and the role technology has played within the pedagogies identified. In this manner, this current review, through drawing on modeling reported in top-tier science education journals over the last decade, provides a unique and needed review that considers pedagogy in terms of the functions, discursive means, and the technologies used to shape student learning. Given this, the following questions guided this research:

Over the past decade (i.e., 2001-2011) . . .

- *What were the purposes or pedagogical functions of modeling?*
- *What types of modeling pedagogies have been used and how were these pedagogies connected to the pedagogical functions of modeling targeted?*
- *When considering the specific pedagogical functions of modeling, what discursive acts were identified as important?*
- *Within the modeling literature reviewed, how often and in what way is technology used in modeling pedagogies?*

It is expected that the analysis and conclusions drawn can be used to inform design, development, and implementation of model-based pedagogies in science classrooms.

BACKGROUND

Purposes or Pedagogical Functions of Modeling Instruction

Modeling instruction, defined for the purposes of this research is instruction that is centered around models, so that students explore, create, test, evaluate, and revise models in singular or iterative cycles in sense making processes within science classrooms. In this regard, modeling instruction may take many forms (e.g., model-based inquiry, model-based reasoning), but there exists some consistency among the forms as amalgamations of how scientist practice science with models and how students develop and use models. These parameters can be seen in science education literature as studies have focused on engaging students in modeling to help students better understand scientific concepts (e.g., Blown & Bryce, 2007; Chang Quintana, and Krajcik, 2009; Niaz, Aguilera, Maza, & Liendo ,

2002). As an example, Chang et al., (2009) investigated the extent to which students' understanding of the particulate nature of matter was enhanced by designing and evaluating molecular animations using a 2D computer modeling platform. In this research, they found that student conceptual understanding was improved through engaging in designing, interpreting, and evaluating their own models when compared to students who only had opportunities to design and interpret models or view and interpret teacher made models. Whether implicit in these example studies or not, there exists a connection here between how scientist leverage models as a set of ideas about how something in the world works (Stewart, Cartier, & Passmore, 2005) and how students can create and use models to explain phenomena as a mechanism for enhancing their understanding of scientific concepts. Modeling instruction also aims to engage students in science practices. One conceptualization of these practices are outlined in *A Framework for K-12 Science Education: Practices, Crosscutting Concepts, and Core Ideas* (NRC, 2012) and include the following eight practices: (1) Asking questions; (2) Developing and using models; (3) Planning and carrying out investigations; (4) Analyzing and interpreting data; (5) Using mathematics and computational thinking; (6) Constructing explanations; (7) Engaging in argument from evidence; (8) Obtaining, evaluating, and communicating information. Model-Based Inquiry is one type of modeling instruction that prioritizes students' engagement in these practices, while inextricably linking this engagement to scientific concept development. An example of this is seen in Windschitl, Thompson, and Braaten (2008) as they focus on Model-Based Inquiry to engage students in asking questions, developing and using models, planning and carrying out investigations, and analyzing and interpreting evidence to construct explanations that are communicated and evaluated by others. Passmore and Stewart (2002) provide another example of modeling instruction in Model-Based Reasoning that attends to the science practices, especially engaging students in argument from evidence. In this study, students developed arguments from evidence found not necessarily in personal inquiries where data is generated through experimentation, but instead in considering ideas emerging from a variety of historical models (i.e., the original works of Darwin, Paley, and Lamarck). Like commonalities between scientists use of models to understand phenomena and students use of models to better understand scientific concepts, the way students are engaged in science practices are also intended to parallel that of practicing scientists for the pedagogical function of enhancing students' facility in these practices.

Finally, another pedagogical function of modeling instruction is focused on developing student

understanding of the nature of models specifically (e.g., Gobert et al., 2011; Prins Bultea, van Driel & Pilot, 2010; Snir, Smith, & Raz, 2003), and the nature of science more broadly (e.g., Coll, France & Taylor, 2005; Windschitl, Thompson, & Braaten, 2008). This was touched upon briefly as the aims of engaging students in the science practices were discussed. But, as is articulated by Lederman (1992; 1998) and supported by research focused on students' understanding of the nature of science (Ackerson et al. 2000), there exists the need for some level of distinction between science practices and the nature of science [and nature of models] as learning outcomes for students:

• *Although these aspects of science overlap and interact in important ways, it is nonetheless important to distinguish the two. Scientific processes are activities related to collecting and analyzing data, and drawing conclusions (AAAS, 1990, 1993; NRC, 1996). For example, observing and inferring are scientific processes. On the other hand, the NOS refers to the epistemological underpinnings of the activities of science. As such, realizing that observations are necessarily theory-laden and are constrained by our perceptual apparatus belongs within the realm of the NOS (Lederman, 1998, n.p.).*

Related to this, just as scientific concept development and science practices have been identified as pedagogical functions of modeling instruction, so too has understanding the nature of models and the nature of science. Gobert et al. (2011) articulate the importance of this purpose as follows:

• *[T]he understanding of scientific models is an important component of students' understandings of the nature of science as a whole....the key connection between the nature of models and the nature of science relates to the belief that models are to be viewed as not completely accurate from a scientific point of view; that is, they are tentative and open to further revision and development (p. 657).*

Gobert et al. (2011) provide an example of research investigating students understanding of the nature of models as they engaged students in using model-based software across three domains of science learning (i.e., physics, biology, & chemistry) and examined whether student understanding of the nature of models increased as a result of engaging in the modeling curriculum. They found that understandings about the nature of models differed across domains. This finding is interesting as it demonstrates where additional research is still needed to further understand the nuanced differences in modeling practices across domains.

Types of modeling pedagogies

In an effort to move toward a more well-defined understanding of modeling as pedagogy, Oh & Oh (2011) suggested five pedagogical conceptualizations for modeling, where the first three were proposed by van

Joolingen (2004) earlier: 1) *Exploratory modeling*, 2) *Expressive modeling*, 3) *Experimental modeling*, 4) *Evaluative modeling*, and 5) *Cyclic modeling*. Collectively, these are referred as modeling pedagogies. Oh and Oh (2011) argued that these five modeling activities reflect how scientists use models in their work and should be given equal intentional consideration in science teaching and learning. Campbell, Oh, and Neilson (2013a) reified these modeling pedagogies through examining how they were embedded in high school physics classrooms to meet targeted student learning outcomes (e.g., conceptual understanding of scientific concepts, science practices, and the nature of models and science). The following is a description of each of the five previously identified modeling pedagogies:

- *Exploratory modeling, where students investigate the property of a pre-existing model by engaging with the model (e.g., changing parameters) and observing the effects.*
- *Expressive modeling, where students express their ideas to describe or explain scientific phenomena by creating new models or using existing models.*
- *Experimental modeling (called inquiry modeling originally in van Joolingen, 2004), where students form hypotheses and predictions from models and test them through experimenting with phenomena.*
- *Evaluative modeling, where students compare alternative models addressing the same phenomenon or problem, assess their merits and limitations, and select the most appropriate one(s) to explain the phenomenon or solve the problem.*
- *Cyclic modeling, where students are engaged in ongoing processes of developing, evaluating, and improving models to complete rather long science projects (Campbell et al., 2013, p. 7-8).*

These modeling pedagogies are based on the notion that science practices, such as modeling considered in this current research, should to be translatable at the level of classroom learning, as a framework for teachers to enact as initial instructional heuristics and for students so that they can exercise and develop facility with the same type of intellectual activities as those of scientists (NRC, 2012).

Discursive acts in modeling instruction

Within the newest standards documents in science education in the U.S. (NGSS Lead States 2013; NRC, 2012), science practices have been identified as one of the three central learning outcomes alongside disciplinary core ideas and cross-cutting concepts. And, as shared earlier, developing and using models has been identified as one of these eight practices. While efforts are made to explicitly articulate the distinctive differences between the eight practices, in reality separating these practices in vivo, both in the work of

scientists and in classrooms, is difficult and likely not warranted. In fact, many researchers see helping students develop and use models as an anchor (Schwarz & Passmore, 2012; Windschitl, 2012) around which disciplinary core ideas, cross-cutting concepts, and science practices can be authentically and meaningfully situated in instruction. Whether models are situated as the learning anchors around which all other science learning outcomes emerge, or they are situated as supportive of other practices positioned as anchors (e.g., constructing explanations or engaging in argument from evidence), there is little debate about the importance of the connection between modeling and other scientific practices, especially discourse. This can be seen in Khan (2007) and Maia and Justi (2009), as examples, as they illuminate how teacher questions connected to inquiry tasks contribute to student learning with models. There are certainly many other possible factors that are important in modeling instruction, but many researchers have identified discursive acts as among some of the most important facets (Bottcher & Meisert, 2011; Buty and Mortimer, 2008; Louca et al., 2011; Passmore & Svoboda, 2012; Windschitl et al., 2008). More specifically, the following are examples of some of these important discursive acts connected to modeling instruction: explanation (e.g., Appling & Peake, 2004; Stieff & Wilensky, 2003), argumentation (e.g., Niaz, Aguilera, Maza, & Liendo, 2002; Schwarz et al., 2009), writing (e.g., Ward & Wandersee, 2002), scientific reasoning (e.g., Buckley et al., 2004; Wendell & Lee, 2010), peer evaluation (e.g., Louca, Zacharia, & Constantinou, 2011; Varelas et al., 2010), peer-to-peer cooperative/collaborative learning (e.g., Ealy, 2004; Fischer, Mitchell, & del Alamo, 2007), and teacher scaffolding (e.g., Cedenio et al., 2010; Hogan & Thomas, 2001).

Our own work in this area (Campbell, Oh & Neilson, 2012) focused on examining important features of discourse occurring in classrooms. To accomplish this, we relied on a discourse analysis framework (Oh & Campbell, 2013) to help identify the most salient types and sequences of discursive modes and their pedagogical functions within model-based inquiry framed instruction. This allowed us to reveal how different types of discourse modes were sequentially connected and embedded in class episodes where the teacher helped students align their models with the canonical knowledge of science.

Another example of the more recent prominence given to discourse within science classrooms more broadly can be found in Louca, Zacharia, and Tzilli (2012) as they identified deficiencies with past discourse analysis that focused mainly on the role of the teacher in asking questions and providing feedback and propose a more appropriate framework for teacher-student discourse interactions supportive of students' inquiries.

Their proposed framework shifts the attention to how teachers identify salient student contributions, decide how to respond to students, and how they actually respond to students as they are engaged in the circuitous act of inquiry. Even though Louca, Zacharia, and Tzialli's (2012) research focuses on supporting students' inquiries without explicit mention of student developing and using models, the distinctions they make about a shifting role for teachers (e.g., responding to student sense-making discourse) is as important to students developing and using models, especially as these models are framed as the students' set of ideas about how something in the world works (Stewart, Cartier, & Passmore, 2005). Given the interdependent links between discursive acts and the practice of modeling, this current literature review sought to understand what could be learned about how discursive acts have been described in modeling research over the past decade. This is important since we see the development of any modeling pedagogies framework necessarily rooted in discursive teacher-student acts and expect that work to support teachers in classrooms will be enhanced as productive discourse episodes and classroom interaction patterns are made known.

Technology and Modeling Instruction

When considering the role of technology more broadly in science teaching and learning, Bell, Gess-Newsome, and Luft (2008) explain that “[m]uch of the value... can be found in its capability to allow students to work with data, to enhance visualization of complex concepts . . . and to facilitate communication and collaboration” (p. 4). As can be seen in this description, most of these affordances are also descriptive of the benefits of engaging students in developing and using models. Therefore, it makes sense that many researchers have leveraged technologies as part of modeling instructional interventions.

One powerful type of technology seen capable of making modeling more accessible to students is computer-based modeling tools (Fretz et al., 2002; Louca, Zacharia, & Constantinou, 2011; Windschitl, 2000). Computer-based modeling tools offer students open-ended exploratory environments supportive of the construction of representations of complex phenomena or systems. One example of this type of technology used as part of an educational intervention can be seen as Louca, Zacharia, and Constantinou (2011) investigated the affordances of Computer-based Programming Environments (CPEs). CPEs, a special type of computer-based modeling tools, offer students microworld environments whereby they can use programming language for developing representations of natural phenomena. In this research, Louca, Zacharia, and Constantinou's (2011) suggested that

computer-based programming environments provide for better modeling-based learning environments, especially “in terms of operationalizing physical entities and physical processes involved in the phenomenon” when compared to other types of model-based learning (e.g., 3-dimensional structures, paper-and-pencil tools, role playing games).

Snir, Smith, and Raz (2003) provide another example of technology for a modeling instructional interventions as they used software to engage students in investigations and evaluating competing models of matter. In this research, they “found that middle schoolers can engage with fundamental ideas about the nature of models, and that engaging them with these ideas helps them internalize the assumptions of the particulate model of matter” (p. 795). Additionally, they observed that the intervention also helped students gain a better understanding of the role of models in explaining a wide range of phenomena.

These examples reveal some of the promise of technology as a medium or tool teachers can use as they engage students in modeling for representing and formulating their understandings of science. But, to date, no comprehensive review could be found examining how frequently and for what pedagogical purposes technology has been employed in modeling research over the last decade. And, especially relevant to this research, no examination has been completed to reveal whether some technologies are more or less capable of supporting certain kinds of modeling pedagogies.

METHOD

To ensure the validity of what is reported in this literature review, a careful set of sequential steps was employed. These sequential steps are revealed here to provide a detailed description of measures undertaken in the explication of our findings.

Identification of articles

In an effort to ensure that the review was informed by the highest quality and impact research, while also beginning the process of narrowing down sources, we identified what we considered the three most influential science education research journals, *Journal of Research in Science Teaching*, *Science Education*, *International Journal of Science Education*, as the source for research that would be reviewed. Additionally, because we were also interested in how often and in what ways technology was used to support modeling pedagogies, we turned to the *Journal of Science Education and Technology* because of its high quality and unique focus on the intersection of science education and technology. We acknowledge that there are certainly more high quality and high impact

journals making a very valuable contribution to science education research, but felt that selection of these four journals with high impact factors, high ISI Journal Citation Report Rankings, and specialized niches aligned to the purposes of this research provided a compelling case for narrowing our search among these four journals.

Within the four journals selected, we completed an exhaustive review by using the keywords *model*, *modeling*, and *model-based* to search abstracts and titles between the years 2001-2011. The initial search yielded 783 articles. Abstracts of each of the 783 identified articles were read. Considering the goal of the review, only abstracts that revealed a focus on modeling as an instructional intervention and contained learner modeling (e.g., K-16 students or pre-service/in-service science teachers as learners) were included. As a result of abstract review based on this criterion, the pool of 783 articles was narrowed to a total of 120 articles. To offer a better sense of how the research article pool was reduced, the following are examples of included articles and excluded articles, with a brief explanation for how each fit or did not fit our criteria:

- *Included Article*

- *Within an introductory undergraduate astronomy course, Keating, Barnett, Barab, and Hay (2002) incorporated opportunities for students to build 3D computer models of astronomical systems. Students worked collaboratively using a software program that provided an intuitive interface for creating models of different parts of the solar system. The researchers investigated whether building the 3D models led to significant gains in the students' understanding of related astronomical concepts. Additionally, the researchers studied the type of conceptual understanding exhibited by the students who learned with the models. Though the study included only 8 students, the type of modeling the students engaged in throughout the study and the purpose for incorporating the models fit the criteria for inclusion within our own study. That is, the students engaged in expressive modeling for the purpose of gaining a conceptual understanding of fundamental concepts within astronomy.*

- *Excluded Articles*

- *We excluded some of articles that included the word model within their abstract from our study. For example, the article by Justi and Gilbert (2002) was excluded because their study investigated teachers understanding and use of models and modelling, but did not reveal a focus on modeling as an instructional intervention and examine an intervention with learner modeling.*

The 120 articles included were read and analyzed, but of these another 39 articles were excluded, because upon reading beyond the abstracts they did not meet our inclusion criteria. In the end, 81 total articles met our criteria and informed our findings, 15 came from the *Journal of Research in Science Teaching*, 13 from *Science Education*, 34 from the *International Journal of Science*

Education, and 19 from the *Journal of Science Education and Technology*.

DATABASE ANALYSES

We used a four-step data analysis process to document the following nine facets of each for the 81 articles included in the review: purpose and research questions, pedagogical function of modeling focused on in research, modeling pedagogies employed, model format used (e.g., 2D computer models, student drawings), discursive acts important in modeling intervention, ways in which technology was used in modeling pedagogies, grade level, content area of intervention, and type of research methodology employed (i.e., quantitative, qualitative, or mixed-methods). While extraction of some of this demographic information from each article was straightforward, there were components requiring more attention and negotiation among the researchers involved. For these components, a hybridized deductive/inductive data analysis strategy was applied as outlined in Table 1. This process was consistent with deductive (Gilgun, 2013) and inductive approaches (Lincoln & Guba, 1985) for the analysis of qualitative data.

The next three steps of our data analysis process were designed to ensure the recursive process of analyzing articles. In the second step, each researcher read 2-3 articles weekly to extract the nine facets from the articles of interest. Any questions related to the coding were documented so that it could be thoroughly discussed in the third step of the data analysis process. The third step was the weekly meetings where our research team was engaged in social discussion and negotiation of coding for each article. In the interim between the meetings, numerous email exchanges occurred where specifics of articles being evaluated were discussed. The meetings and email exchanges allowed for ongoing refinement of the evaluation process for each article and the establishment of consistent methods of coding and reporting. The fourth step involved confirming the coding for each article, as well as annotating and placing all the articles in an archive to accompany the database so that each of the facets of modeling identified was traceable back to the original text. If disagreements or questions arose about a specific article, the researchers revisited the original archived article and sought consensus of interpretation before finalizing the analysis result.

RESULTS

Demographic statistics (i.e., grade level, content area of intervention) and type of research methodology employed are included in Table 2 to reveal the contexts

Table 1. Strategies used by researchers to ensure consistency in data extraction

Components targeted	Initial mechanism for ensuring consistency
Pedagogical function of modeling focused on in research	Pedagogical function was established by referring to [Authors] (2012), whereby the pedagogical function was understood as the kinds of roles the modeling played to assist in achieving instructional goals that the research had in mind. For the majority of articles reviewed, this was identified by examining the outcome measures identified in the research questions.
Modeling pedagogies employed	In-depth descriptors and reification of modeling pedagogies were clarified for all researchers involved in data extraction through careful review and discussion of the modeling pedagogies framework developed by the two lead authors ([Authors], 2013a).
Discursive acts important in modeling intervention	The two lead authors identified and shared common discursive acts found within science education literature to assemble an initial list of acts that could be used for deductive coding of articles. Additional discursive acts were added to the list early on in the review process as acts arose that were not adequately characterized by the initial list. Recursive coding and inter-researcher discussion occurred to complete the results for all the articles.
Ways in which technology was used in modeling pedagogies	The two lead authors identified and shared common technology types within science education literature to assemble an initial list of technologies that could be used for deductive coding of articles. This coding system was applied to identify all the types of technology used in the research reviewed.

and methods from which the findings for the research questions are drawn. As can be seen in Table 2, our review revealed more focus on modeling in 9-12 classrooms (i.e., 31% of articles). There was an approximately equal representation of studies from 6-8 classrooms and 13-16 or undergraduate science classrooms (i.e., 15 & 17%, respectively). And interestingly, within the descriptive statistics the lowest percentage of research on modeling interventions were found in elementary or K-5 classrooms (i.e., 10%). With respect to the content areas addressed in the reviewed research (Table 2), within 9-12 articles, chemistry and biology were the most common content foci (i.e., 11 & 10%, respectively), while physics was a focus also, just not as frequently (i.e., 5%). There was some consistency between the 9-12 and the undergraduate level, with the exception of only one article dealing with student developing and using models at the 13-16 level. Table 2 also revealed that the research methodology most frequently used to investigate modeling interventions was qualitative.

Research Questions 1: What were the purposes or pedagogical functions of modeling?

The most common purpose or pedagogical function of engaging students in modeling was developing conceptual understanding of disciplinary core ideas of science. This was found in 81% ($n = 66$) of the articles reviewed. There was some variation in how this was articulated across studies, with articles found targeting

conceptual ‘reasoning’ and conceptual ‘organization’, as examples. An article focused on developing conceptual understanding can be seen in Verhoeff, Waarlo and Boersma (2008), as they investigated how systems thinking, including modeling, can enable students to develop a coherent understanding of the cell as a basic and functional unit of the organism. In their work, they were able to demonstrate how systems modeling can be introduced in a way that supports students development of a coherent understanding of dynamic biological processes and the structure of biological systems (i.e., the cell and its organelles and the cell as a functional part of a higher level of organization, respectively).

Another purpose identified was engaging students in science practices (i.e., 10%, $n = 8$). An exemplary with this purpose emerged in Kawasaki, Herrenkohl and Yeary (2004). In this study, the researchers observed that through their modeling intervention, students “exhibited some evidence of beginning to think about science using model-based reasoning . . . students began to (1) gain their own understanding of the form of scientific inquiry by acknowledging the problematic nature of the relationship between a theory about and the evidence of a phenomenon, (2) use models as explanations and accept these as conjectural, and (3) recognize that proposing an explanation involves conjectures about theoretical entities different from an observed feature” (p. 1312). However, it should be noted that this purpose was most often referred to as engaging students in ‘inquiry’, because the review drew on research from 2001-2011, before recent standards

Table 2. Demographic statistics of review articles

Grade Level	% of Articles (n)
K-5	10 (8)
8	15 (12)
9-12	31 (25)
13-16	17 (14)
Content Area (9-16)	
High School Biology	10 (8)
High School Physics	5 (4)
High School Chemistry	11 (9)
Undergraduate Biology	1 (1)
Undergraduate Physics	7 (6)
Undergraduate Chemistry	9 (7)
Research Methodology	
Quantitative	23 (19)
Qualitative	51 (41)
Mixed	26 (21)

Note: In some cases articles did not lend themselves to inclusion in this table because the research spanned multiple disciplines and grade levels.

documents, especially in the U.S., revealed a more fleshed out notion of inquiry as science practices.

When considering the modeling research reviewed with a singular purpose of investigating and developing students' understanding and facility with science practices, it can be seen, especially in comparison to research focused on conceptual understanding of disciplinary core ideas of science, that a more limited literature base was identified. In this, care must be taken not to imply that research reviewed was absent modeling practices or that additional research is not available to contribute to this literature base. In fact, a majority of articles within the sample revealed an intervention that engaged students in modeling practices, but most of this research was not categorized here, because it was not focused on understanding or investigating these modeling practices as outcomes. Instead, the article investigated students' conceptual development or their understanding the nature of models specifically or the nature of science more broadly as primary outcomes.

Finally, 30% ($n = 24$) of the articles focused on developing students understanding of the nature of models specifically or the nature of science more broadly. Research by Prins, Bulte, and Pilot (2011) offers an example for understanding the role of models on this epistemological focus. In this research, Prins et al. (2011) found that engaging students in curriculum rooted in authentic modeling practices with an explicit 'meta-modeling layer' proved successful in developing students understanding of models that is consistent with the epistemology of modeling in real science practices. Additionally, a large majority, 85% ($n = 69$), of the research reviewed focused on a single purpose for engaging students in developing and using models, with a great majority of these focusing on conceptual understanding. In addition to singular purposes that were identified in the research reviewed, 14% ($n = 11$) had a dyadic purpose. Within the dual purposed research, conceptual understanding was always identified as one of the two purposes alongside other purposes, such as developing students' facility in science practices or developing their understanding of the nature of models. Finally, only 1 article (1%) (i.e., Schwarz et al., 2009) of the research reviewed explicitly articulated a focus on developing all three of these purposes concurrently (i.e., conceptual understanding, science practices, nature of models/science). In this work, Schwarz et al. (2009) offered the following instructional sequence reflective of purposes they prioritized for modeling:

• *In particular, students construct and revise a model of evaporation and, later, a model of condensation based on empirical evidence of the presence of water vapor in the air. They use newly introduced ideas of water as being composed of smaller bits or particles that spread out in the air so that they cannot be seen (evaporation) and clump together into larger bits of water drops (condensation) under particular conditions. Students' expressed models take the form of written diagrams. The modeling practices within the unit are infused with metamodeling conversations at key moments when epistemic issues are the most relevant (e.g., discussing the evaluation of models when comparing and contrasting different models for the process) (p. 638).*

Within the example, Schwarz et al. (2009) engaged students in instructional sequences that inextricably link knowing, using, and interpreting scientific explanations of evaporation and condensation and evaluating the explanations based on empirical evidence of the presence of water vapor in the air. In addition, student understanding of the nature and development of scientific knowledge is fostered as metamodeling conversations are infused at "key moments when epistemic issues are most relevant". In this and the other research where dual purposes of modeling interventions were investigated, such as Windschitl, Thompson, and Braaten (2007), not only can more be

learned about the individual purposes, but more can also be learned about how these purposes interact to support each other. But, as noted, this was only found in a relatively small number of articles (i.e., 14%, $n = 11$) over the last decade in top science education journals. Finally, beyond these three main purposes, research was also found focused on transferring modeling practices across disciplines. This was seen as Bamberger and Davis (2011) sought to understand middle-school science students' scientific modeling performances across content areas and within a learning progression.

Research Question 2: What types of modeling pedagogies have been used and how were these pedagogies connected to the pedagogical functions of modeling targeted?

In the review, while all five modeling pedagogies originally identified and used for coding were found, the extent to which these pedagogies were employed differed, some more than others. Table 2 reveals the percentage and number of articles within which each of the modeling pedagogies were identified. As can be seen in the table, *Exploratory* and *Expressive modeling* pedagogies were those most often leveraged.

Additionally, like what was suggested by Campbell et al., (2013), the use of one type of pedagogy was not exclusive, but instead frequently two or more modeling pedagogies were combined to address either singular or multiple pedagogical functions. That is, *Expressive* and *Experimental modeling* ($n = 17$), as well as *Expressive* and *Exploratory modeling* ($n = 15$), were most frequently used together.

When these modeling pedagogies were considered in the context of the pedagogical functions of modeling, important trends were revealed. For example, *Expressive modeling* was the most frequently enacted pedagogy when the pedagogical function of the intervention reported targeted developing student conceptual understanding ($n = 27$). An example of *Expressive modeling* used for the purpose of developing student conceptual understanding was found in Cheng and Brown's (2010). In this study, researchers investigated "the spontaneous explanatory models children construct, critique, and revise in the context of tasks in which children need to predict, observe, and explain phenomena involving magnetism" (p. 2367). Beyond this, the research targeting the development of student conceptual understanding also relied on each of the other four modeling pedagogies (i.e., *Exploratory* $n = 16$; *Experimental* $n = 15$; *Evaluative* $n = 16$; *Cyclic* $n = 14$). Urhahne, Schanzeb, Bell, Mansfield and Holmes (2010) offer one example of how *Expressive* and *Experimental modeling* were combined in the service of developing conceptual understanding. In this research, students built a model and conducted an experiment by running

Table 3. Percentage of modeling pedagogies found within articles reviewed

Modeling Pedagogy	% of Articles (n)
Expressive modeling	54 (44)
Exploratory modeling	43 (35)
Experimental modeling	28 (23)
Evaluative modeling	27 (22)
Cyclic modeling	22 (18)

Note: In many cases articles employed multiple modeling pedagogies, leading to an overall n -size greater than the number of articles reviewed since some articles included 2-3 modeling pedagogies. The percentage of articles including each modeling pedagogy was calculated by dividing the number of times the modeling pedagogy was found by the total number of articles reviewed (i.e., 81) since no article included the same modeling pedagogy more than once.

Table 4. Percentage of discursive acts identified as important within articles reviewed

Discursive Acts	% of Articles (n)
Peer-Peer Cooperative/Collaborative Learning	40 (32)
Scientific Reasoning	37 (30)
Teacher Scaffolding	35 (28)
Explanation	26 (21)
Peer Evaluation	11 (9)
Negotiation	10 (8)
Writing	9 (7)
Argumentation	6 (5)
Communication	5 (4)
Dialogicity	4 (3)

Note: In many cases, articles included multiple important discursive acts, which led to an overall n -size greater than the number of articles reviewed. The percentage of articles including each discursive act was calculated by dividing the number of times the discursive act was found by the total number of articles reviewed (i.e., 81) since no article included the same discursive act more than once.

Table 5. Examples of most frequently identified discursive acts found in research reviewed

Discursive Acts	Example
Scientific reasoning	<i>Students constructed a conceptual connection between the specific chemical definitions and the general formula (Connection 1), a visual connection between structural formulas and mental models (Connection 2), and referential connections between this general formula and their mental models (Connection 3) (Wu, Krajcik, & Soloway 2001).</i>
Peer-to-peer cooperative/collaborative learning	<i>Students, working in groups, were asked to describe and interpret annual cycles of temperature, salinity, oxygen, turbidity, and fluorescence data collected from Puget Sound (Winn et al., 2006).</i>
Teacher scaffolding	<i>The interplay between the students' and Neil's [teacher] questions and comments provided the opportunity for reflection and activated the formative assessment feedback loop that encourages knowledge growth. Although student mental model feedback was imprecise/incomplete, Neil could diagnose misunderstandings and clarify the target concept with yet another analogy or by expanding the current analogy (Harrison & Jong, 2005, p. 1146).</i>
Explanation	<i>Students used submicroscopic and symbolic representations in their explanations of chemical phenomena (Treagust, Chittleborough & Mamiala, 2003)</i>

the model in a computer-supported learning environment.

When the pedagogical function was developing students understanding and facility with science practices, which was least frequent (see findings from Research Question 1), *Expressive* modeling was also leveraged most frequently ($n = 9$), whereas *Exploratory* and *Cyclic* pedagogies were found least frequently (i.e., $n = 3$; $n = 3$ respectively). An example can be seen in Louca and Zacharias's (2008) study, where *Expressive modeling* represented an authentic practice of science and served students to learn this practice.

And finally, when focused on developing students understanding of the nature of models specifically or the nature of science more broadly, all pedagogies were used, with little difference in frequency among the five

modeling pedagogies (i.e., *Exploratory* $n = 3$; *Expressive* $n = 5$; *Experimental* $n = 4$; *Evaluative* $n = 6$; *Cyclic* $n = 3$).

Research Question 3: When considering the specific pedagogical functions of modeling, what discursive acts were identified as important?

Table 4 reveals the different types of discursive acts identified as important across all of the research reviewed, irrespective of the specific pedagogical functions of modeling.

As can be seen in Table 4, peer-to-peer cooperative/collaborative learning, scientific reasoning, teacher scaffolding, and explanation were the discursive acts that were most frequently identified as important. But, this feature changed as the pedagogical function of modeling was considered. For example, when the modeling research focused on conceptual understanding, the following discursive acts were identified as important: scientific reasoning ($n = 27$), peer-to-peer cooperative/collaborative learning ($n = 26$), teacher scaffolding ($n = 24$), and explanation ($n = 20$). Examples of how each of the was manifest are described in Table 5. These findings were not dramatically different than those reported in Table 4, but changed when science practices were targeted in the modeling research. That is, the following discursive acts were identified when developing students understanding of science practices was the main pedagogical function: scientific reasoning ($n = 5$) and peer-to-peer cooperative/collaborative learning ($n = 5$). Finally, when considering the nature of models and nature of science as purposes of modeling interventions, peer-to-peer cooperative/collaborative learning ($n = 9$), teacher scaffolding ($n = 9$), and explanation ($n = 8$) were the discursive acts relied upon.

Research Question 4: Within the modeling literature reviewed, how often and in what way is technology used in modeling pedagogies?

Technology was used in 52% ($n = 42$) of the research reviewed. As can be seen in Table 6, computer programs, which included computer simulations and computer visualization tools, stood out most frequently. Other technologies identified in the research reviewed included the Internet, handheld computers, and probeware.

Beyond what is reported in Table 6, when considering whether technology was found more often used in support of one pedagogical function when compared to others, the following descriptive statistics emerged: 52% of conceptual understanding research ($n = 34$); 63% of science practices research ($n = 5$); and 63% of nature of models/science research ($n = 15$). Additionally, of the 36 studies (44%) reviewed that

Table 6. Percentage articles reviewed with technology included

Technology	% of Articles (n)
Computer Program	44 (36)
Internet	4 (3)
Handheld computers	2 (2)
Probeware	1 (1)

Note: The percentage of articles including technology was calculated by dividing the number of times the technology was found by the total number of articles reviewed (i.e., 81) since no article included the same technology more than once.

employed computer programs (e.g., computer simulations & computer visualization tools), 26 studies (32%) used them in the context of *Exploratory modeling*, while 23 studies (28%) in the context of *Expressive modeling*. And, 28 studies (35%) were found enacting one of the other three modeling pedagogies (i.e., *Experimental*, *Evaluative*, and *Cyclic modeling*) or combinations of these three modeling pedagogies with technology. Zimmerman, Raghavan, and Sartoris (2003) offer an example of using *Experimental* and *Evaluative modeling* as learning anchors. In their study, students were engaged in conducting open-ended modeling experiments to depict and test their own ideas about the forces that act when objects are hung from springs and compared and evaluated different models of the same thing by identifying similarities and differences between a given model and the thing it represents.

DISCUSSION

As with the results section, the discussion section is organized by research question, after some initial general discussion about the demographic statistics reported in Table 2. When considering the demographic statistics reported, while it may be tempting to declare that more focus is needed in K-5, 6-8, or 13-16 grade levels, care is taken here not to overstate the importance of these emergent statistics, since these findings may be unduly biased by a higher representation of researchers focused on 9-12 grade level research when compared to other grade levels, especially within the *Journal of Research in Science Teaching*, *Science Education*, *International Journal of Science Education*, and *Journal of Science Education and Technology* searched in this review. However, considering that the newest standards documents outline a prominent role for models as a central learning outcome for students from K-12 classrooms (NGSS Lead States 2013; NRC, 2012), it makes sense that researchers

should focus on modeling into the future in each of these other grade levels (i.e., K-5, 6-8, or 13-16 grade levels).

When considering the disciplines where modeling was found most often in the articles reviewed, chemistry stood out in grades 9-12 and 13-16. This seems fairly understandable, given the prominent role models play in helping students visualize, explain, and predict unseen phenomena and entities, such as atoms and molecules (e.g., Chang et al., 2009). It is however somewhat surprising that only one biology-focused article was found at the undergraduate level, because there was a higher number/percentage of studies at the 9-12 grade level. But, as cautioned already it may be that more research in biology education about models at the 13-16 grade level exists in other journals (e.g., *Journal of Biological Education*, *CBE Life Sciences Education*). Finally among the demographic findings, the fact that the research methodology most frequently used to investigate modeling interventions was qualitative makes sense in the context of research like that of Devetak, Glažar and Vogrinc (2010), who also investigated the research methodologies more broadly across all research included in the three most prominent science education journals and found that qualitative research methods were most prevalent between 2006-2008. Additionally, the other percentages Devetak et al. (2010) found (i.e., qualitative: 45%, quantitative: 27%, mixed: 22%) were very similar to those reported in this research in Table 2.

Research Question 1. What were the purposes or pedagogical functions of modeling?

The majority of the articles reviewed from the sample were focused on developing and investigating student conceptual understanding, especially when compared to considering student understanding and facility with science practices or student understanding of the nature of models. This does not mean to imply that the articles reviewed were absent of rich instantiations of student learning experiences where students were engaged in epistemic practices that could lead to deep epistemological understandings of modeling and science, rather it only notes those facets of the experience which were being investigated. The findings do however indicate that more knowledge is available to speak to how students develop core ideas of science as they are engaged in modeling. In many ways this finding seems logical, since there is acknowledgement that engaging in modeling is not really an epistemic practice of science in the absence of reasoning with and about disciplinary core ideas (c.f., NGSS Lead States, 2013; NRC, 2012) to make sense of phenomena or solve problems.

Another purpose, while not as prevalent, found in one-third of the articles reviewed was a focus on

students' understanding of models. In this, it appears that researchers like Carey and Smith (1993) who called for a focus on engaging students in developing models to cultivate epistemological sophistication were to some extent heard. This is evidenced as researchers have taken note of this important aspect of modeling interventions and have begun to tease apart and target specific constructs of students' understanding about models (e.g., Gobert et al., 2011; Prins, Bulte, van Driel & Pilot, 2010; Snir, Smith, & Raz, 2003). Additionally, it seems to make sense that a significant portion of research investigating modeling has focused on epistemological considerations, since understanding the nature of science has and continues to be an explicitly advocated goal of science education found in national standards documents (e.g., NGSS Lead States, 2013; AAAS, 1989, 1993; NRC, 1996, 2000, 2012)

What was missing to a great extent in the literature reviewed were investigations that focused on how students develop understanding and facility with science practices as they engaged in modeling. While the research reviewed did articulate interventions that engaged students in the epistemic practices of science, little attention was paid to the practice in terms of how students' understanding of the practice or how their facility with science practices developed overtime. These findings are somewhat surprising, given that, an extensive literature has amassed in science education on inquiry, a term that has been used as an umbrella term for practices, as "a decades-long and persistent history as the central word used to characterize good science teaching and learning" (Anderson, 2002, p. 1). However, it should be noted that this is something that is gaining increased attention especially related to modeling practices, as can be seen in Schwarz et al.'s (2009) efforts to develop a learning progression for modeling, and in Mendonca and Justi (2013) and Passmore and Svoboda's (2012) efforts to understand the co-development of modeling and argumentation practices. But, based on the findings of this review it is evident that much more research is needed in this area.

Beyond the singular focused research, dyadic purposed research was also identified, if only in relatively small numbers (i.e., 14%, $n = 11$). As revealed earlier, within the dual purposed research, conceptual understanding was always identified as one of the two purposes alongside other purposes. And, Schwarz et al. (2009), included in the review, explicitly articulated a focus on developing all three of purposes concurrently (i.e., conceptual understanding, science practices, nature of models/science). It should be recognized that this dual and triad focused research not only contributes to the three dominant individual purposes for engaging students in modeling instruction, but it also contributes to visions and understandings of how these purposes can interact to support one another, which is very

important given the priority placed on inextricably linking students' developing conceptual understanding and understanding and facility with science practices and the nature of science in recent national standards documents (e.g., NRC, 2012; NGSS Lead States, 2013). However, because of the paucity of dual or triad focused research identified in this review, there exists a need for more research that focuses on the interactive nature of these purposes for modeling interventions going forward.

Research Question 2: What types of modeling pedagogies have been used and how were these pedagogies connected to the pedagogical functions of modeling targeted?

The findings from this research question are perhaps most important, since a better sense of the pedagogies that have been employed to engage students in developing and using models was revealed. Additionally, this question helped map how the different types of modeling pedagogies have been used for pedagogical purposes. Specifically, *Expressive modeling* emerged as the most pervasive pedagogy. When this modeling pedagogy was applied, students expressed their ideas to describe or explain scientific phenomena by creating new models or using existing models (Campbell et al., 2013). The fact that this was found most prevalent, especially when the purpose of the modeling intervention was conceptual understanding, makes sense if this type of modeling is situated within constructivism as a learning paradigm "in which learners actively create, interpret, and reorganize knowledge" (Gordan, 2008, p. 324). That is, *Expressive modeling* seems to logically provide the space and mechanism for students to vocalize, reconsider, and build on their existing knowledge.

Expressive modeling was also found to be the most commonly used pedagogy when the research targeted developing students' facility and understanding of science practices, even though, as acknowledge already, this pedagogical function was only minimally found in the research investigated. Passmore, Gouvea, and Giere (2014) and Nersessian (2008), among others, argue that developing and using modes is at the heart of the scientific enterprise. If models are defined as sets of ideas for explaining phenomena or solving problems (Stewart, Cartier, & Passmore, 2005), it seems to logically follow that *Expressive modeling*, conceptualized as students expressing their ideas to describe or explain scientific phenomena, would be the most commonly relied upon modeling pedagogy when targeting the development of students' facility and understanding of science practices. Further, beyond just how frequently *Expressive modeling* was found across all research included in the review, it was found that this modeling pedagogy

was also frequently combined with *Experimental modeling* and *Exploratory modeling*. In these cases, data from experiments or previously developed models were enacted as new knowledge that could be integrated into the existing models elicited from students.

Finally, encouraging within these findings is the fact that all the five modeling pedagogies reflecting how scientists use models in their work were found. Through studies such as Passmore and Stewart (2002) where the five modeling pedagogies were combined, these modeling pedagogies are further reified in concert to achieve targeted outcomes in science classrooms. It is therefore recommended that future work in this area should investigate more carefully the roles and effects of combined modeling pedagogies on students' science learning.

Research Question 3: When considering the specific pedagogical functions of modeling, what discursive acts were identified as important?

With this research question, the literature review sought to understand the ways discursive acts have been addressed in modeling research over the past decade. As mentioned earlier, this is important since we see the development of any modeling pedagogies necessarily rooted in teacher-student discourse. It is also expected that the teacher's work in classrooms will be enhanced when productive discursive acts are made known. In this, the findings highlight two important facets of engaging students in developing and using models. Firstly, the consistent identification of explanation and scientific reasoning as important discursive acts demonstrates how closely these discursive acts are connected with modeling. For example, Hogan and Fisherkeller (2005) describe scientific reasoning as "the practice of thinking with and about scientific knowledge" (p. 95). Braaten and Windschitl (2011) also provide a conception of scientific explanations which is founded on employing major scientific theories, seeking theoretical causes for observable events, and utilizing models. Thus, there is a strong relationship between modeling and the two important discursive acts since these practices commonly engage with scientific knowledge in pursuit of understanding scientific phenomena. In addition, scientific reasoning and explanations were identified alongside peer-to-peer collaborative/cooperative learning, another frequently cited discursive act. These discursive acts are important as students worked in groups to develop, manipulate, and understand models, as was seen in Frailic, Kesner, and Hofstein (2009) and Louca, Zacharia, and Constantinou (2011).

The second important facet of modeling highlighted by the discursive acts identified sits with the role of the teacher, such as teacher scaffolding. An example of the

important role of teachers was found in Varelas et al. (2010). In this research, language between the teacher and students acted as a mediator of ideas and action, helping the students progress their models. Also, in our own work ([*Authors*], 2012), the teacher played a centrally important role scaffolding student learning by using exploring discourse connected sequentially with retrieving and negotiating discourse to guide students in aligning their models with canonical knowledge of science.

It should be noted that the ways the articles addressed discursive acts varied with different pedagogical functions and that the number of articles with the purposes of developing scientific practices of modeling and enhancing student understanding of the nature of models was limited. Therefore, there were several discursive acts not identified as frequently in the articles reviewed. Nonetheless, the lack of reference to argumentation seemed to stand out the most, especially given that argumentation is outlined as a central science practice and learning outcome in recent standards documents (e.g., NGSS Lead States 2013; NRC, 2012). This is particularly interesting because the social nature of modeling emerged as peer-to-peer cooperative/collaborative learning was identified as important. Passmore and Stewart's (2002) work is one of a few examples where argumentation was considered significantly in connection with modeling. In this research, students practiced scientific ways of modeling when they were engaged in discussing the adequacy of each other's explanations and how each group used data to support its argument. Considering this exemplar provided by Passmore and Stewart (2002) and other instances with argumentation having been highlighted, more attention should be given to the compatibility and importance of argumentation in the context of modeling instruction in the future.

Research Question 4: Within the modeling literature reviewed, how often and in what way is technology used in modeling pedagogies?

One powerful type of technology capable of making modeling more accessible to students is computer-based modeling tools (Fretz et al., 2002; Louca, Zacharia, & Constantinou, 2011; Windschitl, 2000). These tools offer students virtual environments supportive of constructing representations of complex phenomena or systems and just under half of the research identified employed these types of modeling tools. This result could perhaps be indicative of the ways in which computer based-modeling tools were more readily designed for examinations of pre-existing models and the creation of new ones. For example, Pata and Sarapuu (2007) used computer whiteboards as expressive environments where students worked in

groups to create representational artifacts. Additionally, they used simulations as exploratory environments where students could study the effects of changing variable values on specific models. This is just one example of the compatibility of technology and modeling that helps to explain why so much of the modeling research examined included technology. Brady, Holbert, Soylu, Novak, and Wilensky (in press) further elaborate the natural resonance between technology and model-based learning as they articulate how computational models created by students act as depictional artifacts of students thoughts (Lesh & Doerr, 2000), such that these artifacts can serve as a model of student thinking and how students intergrate interdisciplinary knowledge within problem contexts (Martin, Hjalmarson, & Wankat, 2006).

In our previous work ([Authors], under review), we have noted how technology shaped and reshaped lives and societies through the predominance of social networking, gaming, and mobile phones as fixtures of youth culture (Ito et al., 2008), through spawning the emergence of new scientific fields (Hey, Tansley, & Tolle, 2009), and through science being transformed with technology (Sabelli, 2006). In this current research, it appears that technology has and can do the same in the future if science educators continue to consider new and innovative ways of engaging students in developing and using models. In other words, through the research reviewed, a strong base is available to support our recent assertion that “technology should be an important modern aspect of science teaching and learning” ([Authors], under review).

CONCLUSION AND IMPLICATIONS

This literature review drew on modeling research reported in top-tier science education journals over the last decade to consider the purposes or pedagogical functions of modeling, the types of modeling pedagogies used, the discursive acts identified as important in modeling, and how often and in what ways technology was used to engage students in developing and using models. As reported earlier, the journals that served as the main data sources for this review, *Journal of Research in Science Teaching*, *Science Education*, *International Journal of Science Education* and the *Journal of Science Education and Technology*, were selected because of their influence and focus on science education research. We acknowledge that there are certainly more high quality and high impact journals making a very valuable contribution to science education research, however we elected to focus our efforts and resources on reviewing research in these four journals since we felt that these

journals, with high impact and specialized niches aligned to the purposes of this research, could provide a representative sample of modeling instruction.

As a result of the review, when considering the purposes or pedagogical functions of modeling, it was found that conceptual understanding was most common target of research, with nature of models and science as the next most targeted outcome. And, it was noted that only a minimal amount of focus was placed on developing students’ facility and understanding of science practices, at least as a targeted outcome for the interventions included in the review. When considering which modeling pedagogies were observed within the literature over the last decade, *Expressive modeling* was the most frequently used and sequences that combined *Exploratory* and *Experimental* modeling were the most frequently found combination of modeling pedagogies. Additionally, while some types of modeling pedagogies were found more frequently in comparison to others (e.g., *Expressive modeling* compared to *Cyclic modeling*), visions and understandings about each pedagogy were nuanced within the literature.

When the discursive acts identified as important in modeling were considered, scientific reasoning and explanation along with peer-to-peer collaborative/cooperative learning were among those most frequently found. This seemed related to the how intricately connected these specific discursive acts are with modeling. Argumentation, a discursive act prioritized in recent standards documents (NGSS Lead States 2013; NRC, 2012), was not observed frequently in the modeling research reviewed. Finally, in terms of technology used to engage students in developing and using models, it was revealed that technology was leveraged in approximately one-half of the research reviewed. More specifically, *Expressive* and *Exploratory modeling* pedagogies were found most often supported or mediated by computer technology, while *Experimental*, *Evaluative*, and *Cyclic modeling* pedagogies did not emerge frequently.

This literature review provides a unique and needed review that considers pedagogy in terms of the functions, discursive means, and the technologies used to shape student learning. Through this work, we have been able to understand the modeling pedagogies that have been enacted and investigated, the pedagogical functions of these pedagogies, the critical discursive acts within these functions and pedagogies, and the role technology has played within the pedagogies identified. Given this, Table 7 outlines implications of the findings for research and educators.

Table 7. The implications of the findings for research and educators

Specific Findings	Implications of Finding for Research and Educators
Conceptual understanding was most common target of research, followed by the nature of models. Only a minimal amount of focus was placed on developing students' facility and understanding of science practices.	These findings point to the importance of modeling instruction as a tool/resource for developing students' conceptual understanding and the nature of models/science. It identifies a need for increased attention in the literature to how students' facility and understanding of science practices is understood as an outcome of modeling instruction.
All modeling pedagogies were found represented in the literature reviewed.	This finding indicates that visions, understandings, and mechanisms for engaging students in each modeling pedagogy that are related to the way scientists engage with models can be found in the literature to ground future research and provide mechanism for engaging students in modeling in classrooms.
Discursive acts like scientific reasoning and explanation along with peer-to-peer collaborative/cooperative learning were those most frequently found. Argumentation was not observed frequently in the modeling research reviewed.	These findings document the discursive nature of engaging students in developing and using models. With respect to argumentation, this point to a need for increased focus in this area, given the fluidity in which scientists move across the spheres of science practices that include modeling and explanation as one sphere and argumentation and evaluation as another (c.f., NRC, 2012, Figure 3-1, p. 45)
Technology was leveraged in approximately one-half of the research reviewed and <i>Expressive</i> and <i>Exploratory modeling</i> pedagogies were found most often supported or mediated by computer technology.	These findings point to the compatibility of technology and modeling and point to those types of modeling pedagogies that have, to date, helped frame the role of technology within modeling contexts.

Collectively, in this research, we sought to more generally understand the pedagogical functions that modeling has played in science instruction and research. Our aim was also to support the development of our modeling framework in coordination with discursive acts and technology. We believe that this emerging framework can provide teachers with a well-defined understanding of modeling as pedagogy to help students developing and using authentic scientific practices. As a result of this review, we are better positioned to base our framework on the rich body of literature to support what we think are essential components of meaningful modeling instruction (i.e. pedagogical functions of modeling, modeling pedagogies, discursive acts, and technology). This work can also inform other researchers of insight into how their research sits among others' work, particularly within the focus of modeling pedagogies we shared in this review.

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*References marked with an asterisk indicate studies included in the review. Note: All articles included in the review were not included in the references, only those specifically referenced in the text. A list of all articles included in the reference can be obtained by emailing the corresponding author.

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