Modeling in Science Education: A Synthesis of Recent Discovery Research PreK-12 Projects

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American Institutes for Research

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Executive Summary

Context and Our Focus

The report summarizes the results from recent research and development projects that focused on modeling and simulations in science education. The Discovery Research PreK-12 (DRK-12) program of the National Science Foundation funded these projects as part of its mission to support the teaching and learning of science, technology, engineering, and mathematics (STEM) in grades PreK-12 through innovative educational approaches.[1] This report synthesizes findings from 33 articles produced by 18 DRK-12 grants awarded from 2011 to 2015, all of which funded development of resources or instructional practices to support student modeling in PreK-12 science education.

Findings

This synthesis had two broad purposes: to describe 18 modeling-focused DRK-12 projects with respect to the resources they studied and the methods they used, and to summarize the new knowledge these projects produced related to modeling instruction. The following were the major findings about resources studied and methods used:

- **Most projects studied digital modeling resources.** All projects included in this synthesis studied resources for student modeling, and the majority studied a digital modeling resource that students used to access digital simulations of natural phenomena. Most projects also incorporated nondigital resources in the form of curriculum materials supporting student use and construction of physical models. Few projects went beyond providing teachers with supplemental units or lessons, with only three projects providing professional development resources.
- **Most projects used descriptive designs and examined student outcomes.** The projects in this review incorporated various studies and methods. However, most projects used descriptive designs such as case studies and naturalistic observation rather than comparison group designs to analyze relationships among modeling resources and student outcomes. Nearly all projects incorporated a measure on student outcomes, the most frequent of which were written assessments of disciplinary content knowledge. A minority of projects measured student modeling practices and skills through a variety of methods examining student work. Relatively

[1] The National Science Foundation provided a grant to the American Institutes for Research (AIR) to synthesize findings from DRK-12–funded research and development in several key areas of STEM education. AIR also is producing reports synthesizing DRK-12–funded research on other topics besides modeling, such as pedagogical content knowledge, scientific argumentation, and elementary science education.

few projects measured teacher outcomes such as pedagogical knowledge or instructional practice.

These 18 DRK-12 projects produced knowledge on how to support student modeling in various PreK-12 science settings, with respect to promising instructional approaches. These findings include the following:

- **Teacher scaffolding supported model construction and use.** Teacher instructional moves supported student modeling, scaffolds for specific modeling tasks decreased student challenges, teacher mediation and student discussion enhanced use of digital modeling resources, and teacher scaffolding enhanced student use of computer simulations.
- **Embedded scaffolds supported modeling with feedback and guidance.** Much of the simulation and modeling software developed by these projects incorporated various user-friendly supports, including timely and relevant informational prompts, procedural supports, and direct feedback on student measurements. With embedded scaffolding, students' work reflected more advanced uses for modeling and simulation software over time as well as improved content knowledge.
- **Technological affordances enhanced the perceptual experience of simulations.** A few projects included studies on the effect of technological enhancements on simulation user-experience. Students using technological affordances generally spent more time using the simulations and demonstrated greater scientific content knowledge than those who used simulations without such enhancements.

The 18 projects in this review generated knowledge about the relationship between modeling and student scientific knowledge, skills, and attitudes. These projects included studies demonstrating increased student content knowledge and improved science-related skills after using simulations or participating in model construction, as indicated by pre- to post-test change. A few studies also reported initial evidence for improved student attitudes and interest in the topic after constructing and testing models.

Implications for the DRK-12 Portfolio

This review highlights opportunities for future research on modeling and simulations, including potential gaps in the DRK-12 portfolio. Most of these projects focused on developing student resources, such as curriculum materials, modeling platforms, and computer simulations. Nearly every project focused on student use of these simulations rather on their development, evaluation, or revision. A small number of projects described the learning progressions for student modeling over the course of a unit. Future research could expand the scope for identifying learning expectations over an entire year and could support development of a more comprehensive curriculum. With further research and development, it also may be possible to look beyond student modeling quality as an outcome and develop assessment resources that would be feasible for teachers. Furthermore, relatively few projects provided evidence on teacher-focused supports and interventions (i.e., developed or tested professional development). The DRK-12 portfolio could benefit from examining how to promote teacher pedagogical skills related to modeling-based instruction. Overall, there is space to examine a wider scope of both student teacher and student outcomes such as scientific reasoning, science process skills, meta-modeling knowledge, or attitudes toward science learning as well as program implementation. Future DRK-12 learning involving these resources could incorporate research designs focused on larger sample sizes and gathering evidence on effectiveness and feasibility of implementation across classrooms and contexts. Exploring these topics related to modeling and simulations could help support DRK-12's mission to significantly enhance PreK-12 STEM teaching and learning.

Why this topic?

Modeling of natural phenomena is critical to the practice of science and engineering (Louca & Zacharia, 2012; National Research Council [NRC], 2012). A model is an explicit representation of a scientific phenomenon, describing how elements of a system interact and defining relationships among variables to be able to explain and predict events (Clement, 2000; NRC, 2012). Scientists and engineers develop, test, refine, and use models to investigate phenomena and engineer solutions. Models are not meant to be copies of physical phenomena; rather, they are abstractions that highlight the elements and relationships among them that are most relevant to the purposes of the investigation (Oh & Oh, 2011; Schwarz et al., 2009). This abstraction helps people—scientists, citizens, and students—understand scientific concepts and apply theories to specific situations (Gilbert, 2004). Models accomplish this purpose through nonverbal and visual representations—which are effective in communicating complex phenomena and relationships that are not readily observable (Oh & Oh, 2011). A model enhances scientific reasoning by serving as a cognitive framework for understanding and interpreting new information (Nersessian, 1999).

The Next Generation Science Standards (NGSS) include “developing and using models” among the science and engineering methods that students should learn as they explore disciplinary core ideas (NGSS Lead States, 2013). Some teachers have struggled to adopt this modeling-based learning approach. One reason is that it represents a departure from traditional science education, in which students memorize explanations of phenomena, master a vocabulary of scientific terms, and conduct labs with known outcomes (Osborne & Dillon, 2008; Weiss et al., 2003; Windschitl & Stroupe; 2017). Although the NGSS were released in 2013, they reflect more than 3 decades of research on effective science education for Grades K–12, as summarized in the *Framework for K-12 Science Education* (i.e., the *Framework*; NRC, 2012). The *Framework* and NGSS represent a “redefinition of…what it means to be proficient in science” that “rests on a view of science as both a body of knowledge and an evidence-based, model-building enterprise that continually extends, refines, and revises knowledge” (NRC, 2007, p. viii). In particular, the *Framework* states that by the end of high school, students should be able to:

- Construct drawings or diagrams as representations of events or systems.
- Represent and explain phenomena with multiple types of models and move flexibly between model types when different ones are most useful for different purposes.
- Discuss the limitations and precision of a model, suggest ways in which it might be improved to better fit available evidence, and refine a model to improve its quality and explanatory power.

- Use (provided) computer simulations as a tool for understanding and investigating aspects of a system, particularly those not readily visible to the naked eye.
- Make and use a model to test a design, or aspects of a design, and to compare the effectiveness of different design solutions.

The practice of modeling closely relates to other science and engineering practices included in the NGSS. For example, the process of creating models involves *understanding relationships* among elements in a system. Models assist students in *constructing explanations* and *engaging in argumentation* as they consider cause and effect for system processes. Students also *use mathematics and computational thinking* as they create computational models to represent their conceptual models. Illustrating the centrality of modeling, intensive professional development in modeling instruction fosters greater self-reported implementation of all NGSS science and engineering practices (Haag & Megowan, 2015).

What is modeling-based learning?

Researchers have discussed different instructional approaches through which students engage in modeling-based learning (MBL). Although there are different approaches to MBL, they tend to share the following steps of an iterative process (see, for example, Louca & Zacharia, 2012, and Schwarz et al., 2009; also see Exhibit 1):

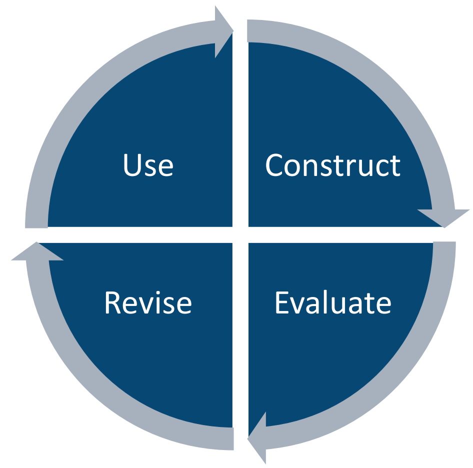
1. **Construct:** Students construct a model based on observations and previous knowledge. During this step, students decompose a phenomenon into its component systems and examine their causal relationships. Students specify what variables to include and express the relationship among these variables.
2. **Evaluate:** Students evaluate the model based on objective data they collect or identify, or based on their previous expectations. Testing occurs when using computational models to generate output.
3. **Revise:** Students revise the model to improve its explanatory and predictive power. Model revisions can include adding or deleting variables or modifying the relationship (e.g., changing the slope of a linear relationship or changing a linear relationship to a quadratic relationship).
4. **Use:** Students use the model to make predictions in a new situation. For example, students who use a model to predict the motion properties of a ball that is thrown can use the same model to predict the motion properties of a person on a swing.

Metamodeling knowledge may be a precondition for engagement in MBL. This knowledge comprises an understanding of the nature of models, purpose of models, and criteria for evaluating and revising models. In short, knowing what models are used for helps students to engage in the practices, and vice versa (Schwarz et al., 2009).

What practices and resources support student modeling?

Instructional practice and digital curriculum tools each play an important (and interactive) role in supporting MBL. With regard to instruction, teacher support and scaffolding are critical for ensuring that students progress through the steps of MBL (Manz, 2012; Vo et al., 2015). When students are able to propose viable ideas about the topic being studied, the teacher acts as a moderator, helping students clarify their ideas (Halloun, 2007).

Exhibit 1. Four Phases of the Modeling Cycle



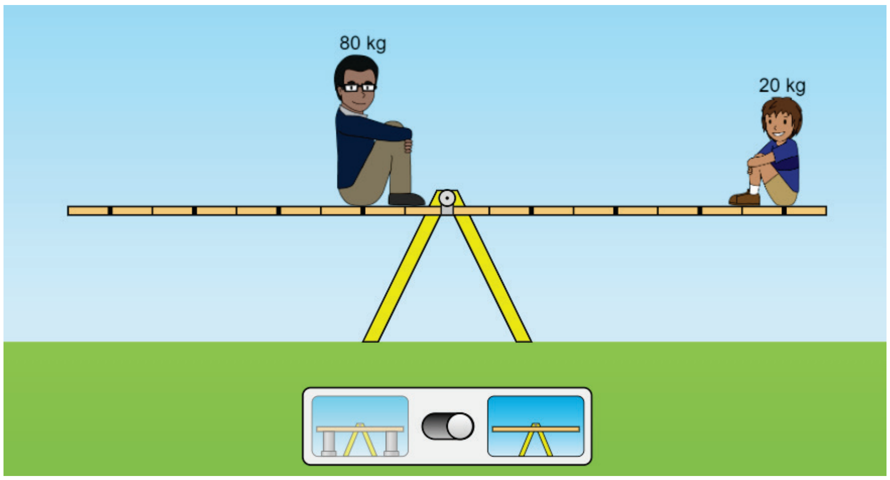
Source: Author's construction based on Schwarz et al. (2009).

To provide this support, teachers need an understanding of appropriate pedagogies for modeling instruction (Akerson et al., 2011; Gilbert, 2004). Given the substantial shifts in teaching represented by the NGSS (Windschitl & Stroupe, 2017), many teachers are in the beginning stages of developing the pedagogical content knowledge to implement modeling (Kang et al., 2018). As Pasley and colleagues (2016) noted in a primer on the science and engineering practices, "there is limited guidance on what these practices should 'look like' in the classroom (p. 1)." Modeling in particular ranked low among the science and engineering practices with respect to teacher knowledge (Kang et al., 2018). Case study research has indicated that teachers often struggle with encouraging model prediction, discussion, and revision (Windschitl et al., 2008). Teachers also need to understand the purpose of models. Teachers who view models primarily as a means to describe phenomena are less likely to ask students to create and evaluate their own models (Oh & Oh, 2011; Van Driel & Verloop, 1999).

In light of these challenges, some researchers have proposed instructional frameworks for teacher facilitation of student development, use, testing, and revision of models. Building on Karplus and Butts's (1977) learning cycle, Hestenes (1987) introduced a modeling cycle with a three-phase structured process in which teachers guide students to (a) explore the relationship among variables, (b) test and revise models, and (c) use models to solve problems. Halloun (2007) also developed a modeling cycle in which teachers encourage students to recognize shortcomings of their current knowledge and thereby gain motivation to construct a new model.

Several digital resources support the development, use, and dialogue about models (Shen et al., 2014). Computer-generated models of natural phenomena, known as simulation software, support students in constructing, testing, and revising models (Smetana & Bell, 2012). For example, PhET Interactive Simulations provides digital simulation tools where students can manipulate the values of input variables to observe the effect on output variables across all major science disciplinary areas (Exhibit 2).

Exhibit 2. PhET Interactive Simulations, Balancing Act



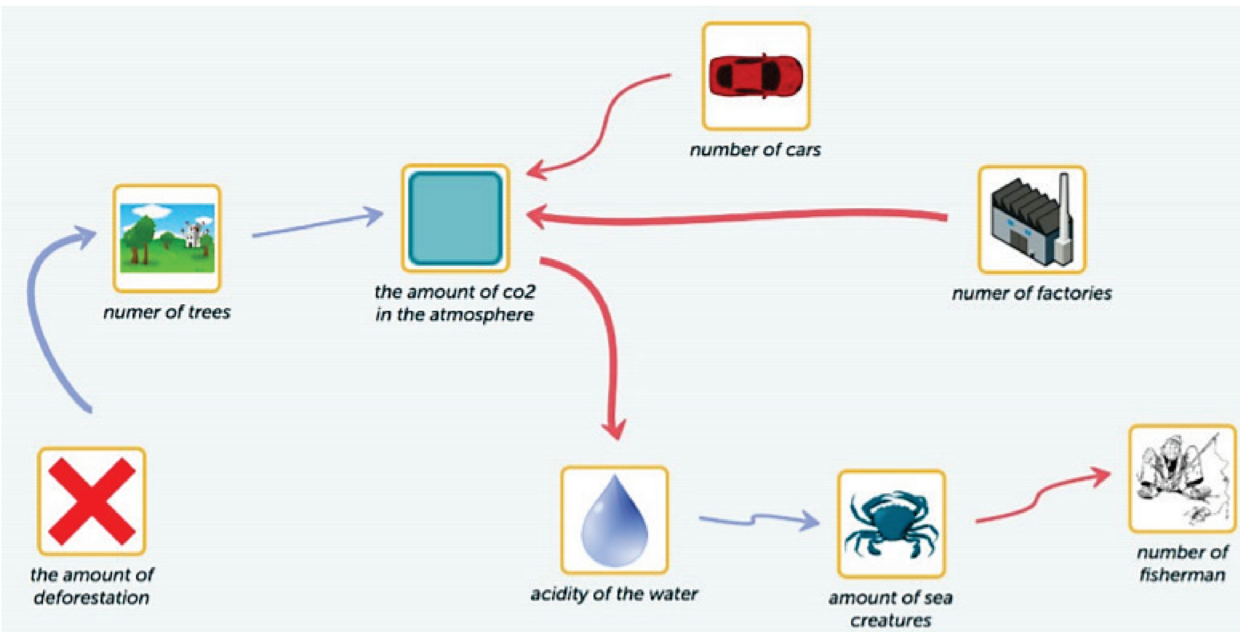
Source: PhET Interactive Simulations, Balancing Act. Available at
https://phet.colorado.edu/sims/html/balancing-act/latest/balancing-act_en.html

These simulations are intended to help students understand phenomena and thereby support construction of conceptual models. Because simulations provide immediate results, they allow students to conduct multiple trials to test and refine their models (Windschitl & Andre, 1998). A review of the literature on virtual experiments found that they enhance student learning when used as a supplement to real (i.e., not simulated) experiments; this effect is most pronounced for students who have experienced difficulties in learning science (Rutten et al., 2012).

Teachers play an important role by scaffolding student use of simulations that are used for model construction and testing. Because simulation software can include dozens of parameters, teachers need to help students to focus on the relevant information for constructing or testing their models (Lowe, 2004). Teachers can provide several types of scaffolds for the use of simulation software, such as heuristics, background information, and procedural information (Rutten et al., 2012). These supports have an impact on conceptual learning (e.g., Barab et al., 2009) and the quality of modeling (Manlove et al., 2009).

Another type of digital resource are digital modeling platforms that support the different phases of the modeling cycle: learning about a natural system (such as the water cycle), creating a conceptual model that depicts variables in a system and their relationships, creating a computational model, and analyzing data. For example, the SageModeler platform allows students to create conceptual models of ocean acidification (see Exhibit 3; Bielik et al., 2018). As with simulation software, teacher scaffolding supports student use of these resources for completion of the modeling cycle. For example, one study found that when teachers provided students with scripts and question prompts, students delivered more substantive critiques of models created using this platform (Chang et al., 2010).

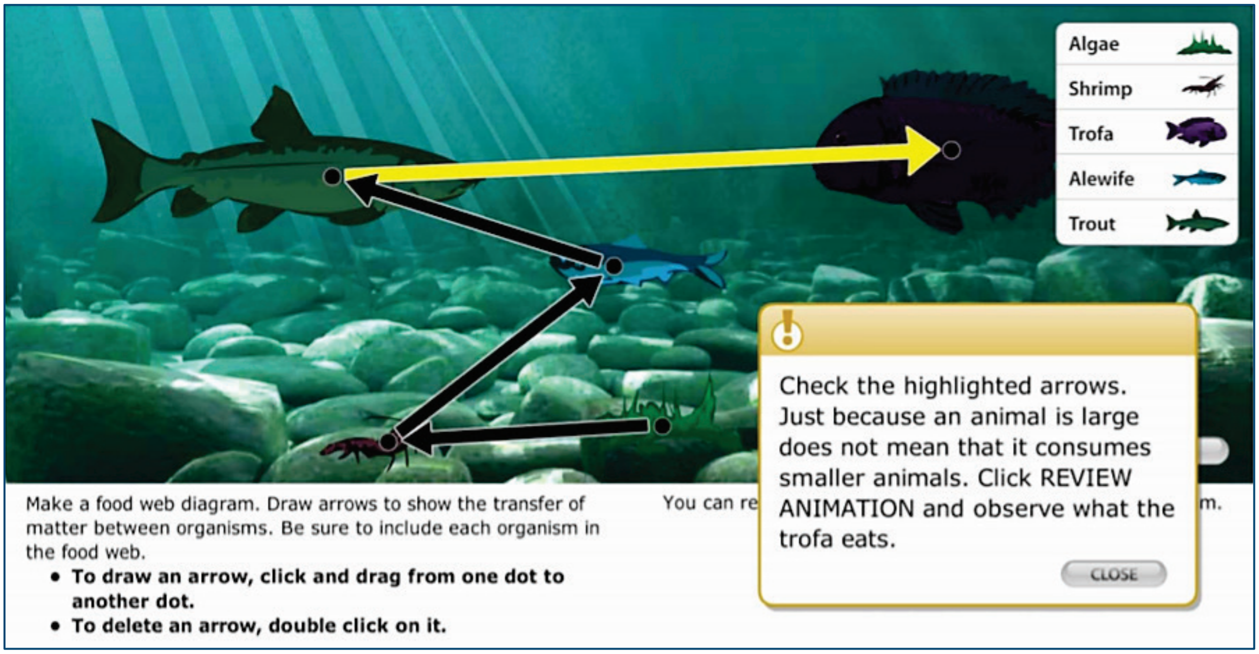
Exhibit 3. Student Model of Ocean Acidification Created Using SageModeler



Source: Bielik et al., 2019.

The digital platform itself may incorporate scaffolds or other design features intended to enhance their usability. These may include textual cues highlighting relevant information, especially for students with lower levels of prior knowledge, to keep them focused on the important features (e.g., Quellmalz et al., 2016; see Exhibit 4). Related to these scaffolds, some platforms have several features for promoting collaboration, including the ability to link up different systems that are independently modeled by different groups of students (e.g., Mr. Vetro, as described by Ioannidou et al., 2010), and online discussion forums on the WISE platform (Linn & Eylon, 2011) that allow different teams to discuss and critique their models.

Exhibit 4. Digital Modeling Tool Providing Textual Feedback on Conceptual Model



Source: Quellmalz et al. (2016).

In summary, modeling is a central scientific practice, and modeling-based learning helps students understand scientific concepts. Digital modeling resources show promise in being able to support students in the modeling cycle. Inasmuch as modeling-based learning represents a departure from traditional science education, it is crucial to prepare teachers for modeling instruction. Further synthesis research is useful to generate themes and findings about instructional supports for student modeling across a body of research. Recent investments by the National Science Foundation (NSF), the focus of this study, provides an opportunity to synthesize findings from resources and interventions for modeling instruction.

What did the synthesis examine?

> From 2011 to 2015, the DRK-12 program funded or cofunded 18 projects relating to modeling-based instruction, totaling $21,654,127 awarded.

The DRK-12 program aims to enhance STEM learning and teaching in the PreK-12 grades through investment in the research and development of STEM education innovations and approaches. Our review team identified modeling as one key area of NSF investment in K–12 STEM education, based on a structured review of recent award abstracts.[2] We found that in the 5 years spanning 2011 to 2015, the DRK-12 program funded or cofunded 18 projects relating to modeling, totaling $21,654,127 awarded. Based on our

[2] This report's synthesis on NSF-funded modeling research comes from a broader NSF project, *Advancing Methods and Synthesizing Research in STEM Education* (DRL-1813777), which aims to synthesize evidence of innovation and discovery in recent DRK-12 projects.

literature search, these projects produced a pool of 34 research reports that provided an opportunity to study and synthesize modeling as key science and engineering practice in STEM education research. The following is a summary of the research questions and the planned approach to answering these questions:

5. ***What resources for modeling instruction did projects study?*** The synthesis categorizes the types of professional resources developed, such as professional development and curriculum materials, and the digital resources supporting MBL, such as modeling platforms or simulation software (using the coding scheme of D'Angelo et al., 2014). The synthesis also summarizes the types of modeling activities supported by the instructional materials or instructional methods developed by each project. We categorize activities with respect to the MBL framework (Schwarz et al., 2009) as well as with respect to the ways that students construct models.
6. ***What research methods did projects use to study modeling interventions and resources?*** The synthesis describes research methods with respect to study design, data source, student outcomes measured (adapting a framework developed by Halloun, 2007), and teacher outcomes measured (adapting the coding scheme of CADRE, 2014).
7. ***What new knowledge did studies produce about effective instructional approaches and resources for supporting student modeling outcomes?*** The synthesis describes new knowledge produced by projects about how modeling skill develops, including effective instructional approaches and resources for supporting development of this skill. The outcome of interest for this question is student acquisition of modeling skill and meta-modeling knowledge (e.g., Schwarz et al., 2009).
8. ***What new knowledge did studies produce about the relationship between modeling and scientific knowledge, skills, and attitudes?*** The synthesis describes new knowledge about how modeling-based instruction relates to scientific knowledge and skill (other than modeling itself) as well to student attitudes about science.

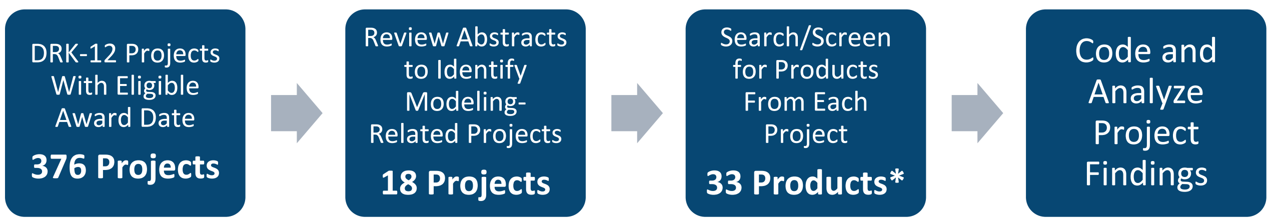
Our Synthesis Approach

We examined DRK-12 projects with an original award date spanning January 2011 to December 2015 to focus on recently completed or close-to-completion projects. We downloaded the award abstracts for all DRK-12 awards in this date range using NSF's website (https://www.nsf.gov/awardsearch/). When screening projects for their relevance to modeling, we searched for award abstracts that contained the word "simulat*" or "modeling" ("model" was too broad of a term, but "modeling" was often relevant to students' use of models). After reviewing 64 project abstracts that included these terms, we determined that 18 were potentially relevant to a more focused set of inclusion criteria aligned to the research questions:

projects that (1) developed instructional resources, such as models or simulations, for classroom use; (2) provided support for teacher use of models or simulations; or (3) observed students engaged in scientific modeling.

We then systematically looked for publications that these 18 projects generated and sent e-mails to all project principal investigators (PIs) asking for additional products that our searches may have missed. For each NSF project, we identified between one to three products that were most closely related to the three criteria and were most completely reported (i.e., favoring peer-reviewed journal articles over conference presentations or short project summaries). This process yielded 33 study reports (i.e., products) that formed our synthesis of the findings from the 18 projects (Exhibit 5). Appendix A provides more detail on the synthesis methods, and Appendix B lists the 18 projects and the 33 associated research products.

Exhibit 5. Overview of Our Synthesis of 27 DRK-12 Projects Related to Modeling



*More than 50 products were identified from these 18 projects, but for feasibility, we restricted our synthesis to the one to three products per project that were most directly related to modeling and most completely reported.

We structured the review, coding, and analysis of the sources to align with the four research questions. We coded and analyzed the products using two approaches: (a) structured coding based on a priori categories (e.g., type of study design), informed by coding protocols from prior systematic reviews on modeling (CADRE, 2014; D'Angelo et al., 2014; Halloun, 2007; Schwarz et al., 2009); and (b) qualitative narrative review of project findings (supported by the software NVivo). The coding structure appears in Appendix C.

The following sections correspond to each of the four research questions. We also include spotlights of projects that highlight their research methods and findings about modeling resources.

What resources for modeling instruction did projects study?

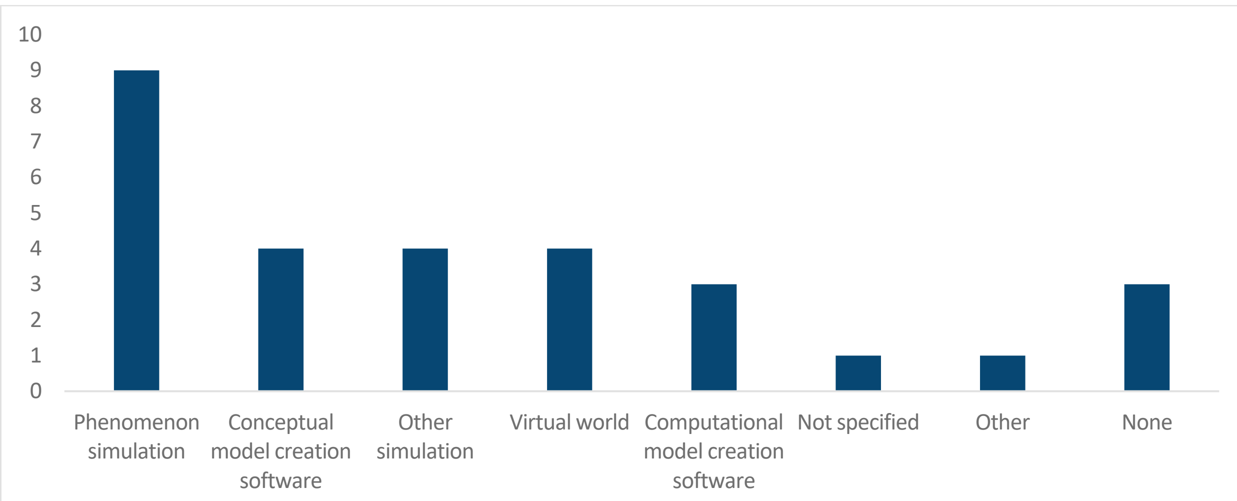
The 18 DRK-12 projects are described with respect to the student modeling resources they developed and tested, the types of modeling activities they supported or tested, and the professional resources they developed.

Student Resources and Modeling Activities

Projects developed digital and nondigital modeling resources for students, and observed students engaged in a range of activities related to modeling.

Most projects studied digital modeling resources. Among the 18 projects, all studied some type of resource for student modeling.[3] Fifteen projects studied a digital modeling resource, all of which included some type of digital simulation. The most common type of digital resource, studied in nine of 18 projects, was a simulation of natural phenomena (Exhibit 6). Four projects also included digital platforms for constructing conceptual models; three of these four included resources for creating computational models.

Exhibit 6. Simulations of Natural Phenomena Were the Most Common Type of Modeling Resource



Fourteen of the 18 projects included nondigital modeling resources, such as curriculum materials to support student modeling activities. For example, one project created a detailed lesson plan for a water filtration activity to serve as a physical model of the water cycle (Kilpatrick et al., 2018). These projects differed with respect to the types of modeling activities and model representations in which students engaged.

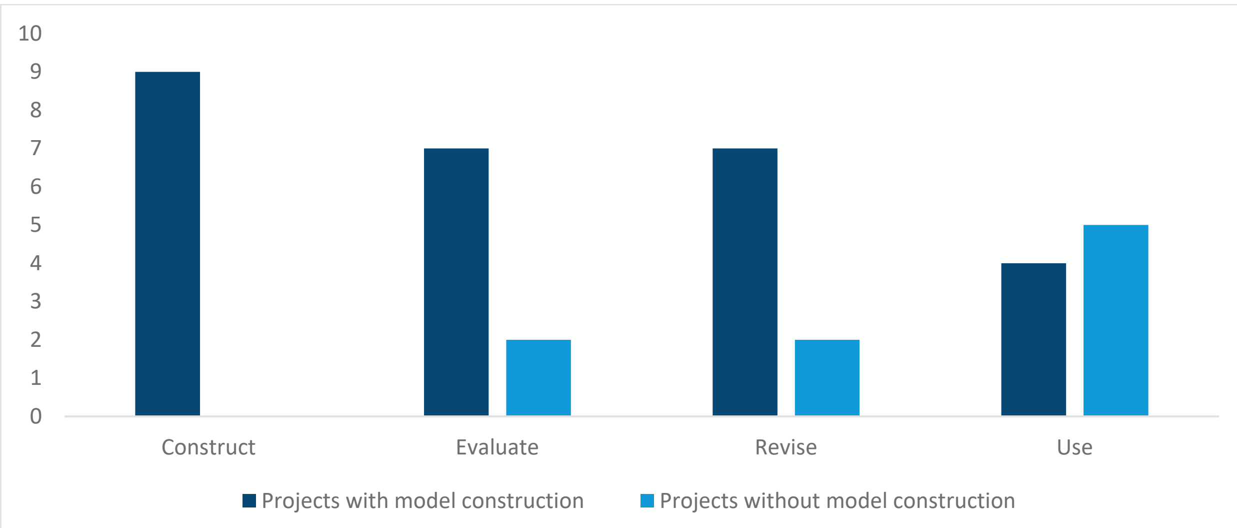
The projects most frequently studied students using computer simulations to explore phenomena. The most common type of modeling activity in projects was using models to explore scientific phenomena or engineering principles (16 of 18 projects). In the vast majority

[3] This was not simply an artifact of the article selection process. Our inclusion rules did not specify curriculum or instructional materials; projects that examined teacher practices related to modeling (without developing or studying student-facing materials) also would have been included.

of these projects, students used models that were part of computer simulations (15 of 16 projects).

We considered how frequently projects studied student participation in each of the four components of the modeling cycle (i.e., constructing, evaluating, revising, and using a model). These components received similar emphases in the research, with each being studied by nine projects (Exhibit 7). Among projects in which students constructed models (such as those in which they used simulation software), students typically also evaluated and revised the models they constructed. Among projects in which students did not construct models, they typically used models to make predictions (Exhibit 7).

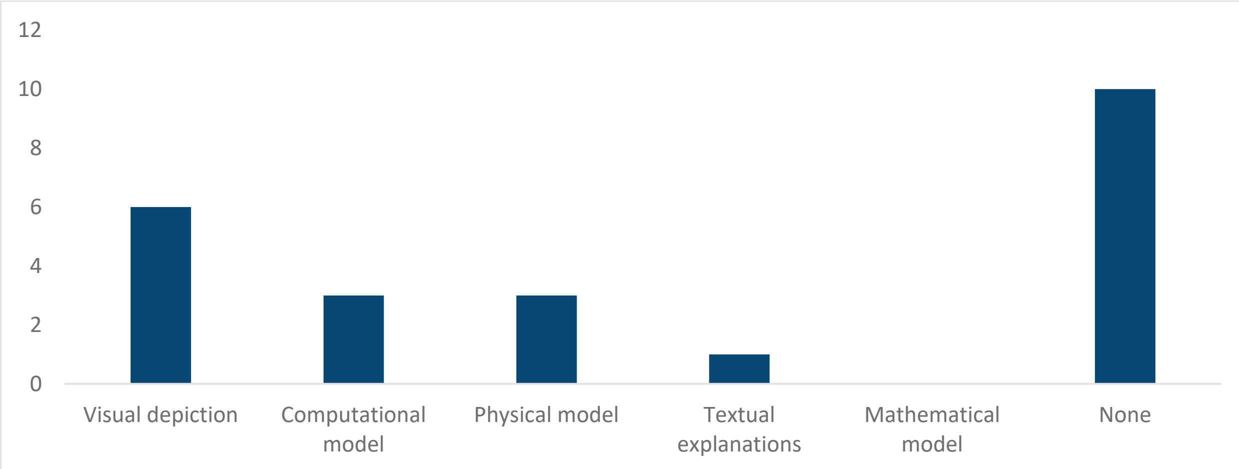
Exhibit 7. Number of Projects in Which Students Engaged in Different Phases of the Modeling Cycle



Note. Categories are not mutually exclusive. *N* = 18.

Students engaged in different types of activities to depict models. Across the nine projects in which students constructed models, students engaged in different types of activities to depict conceptual frameworks. The most frequent approach, used in six projects, involved visual depictions, such as illustrations, drawings, and concept maps (Exhibit 8). In three projects each, students created a computer model or physical model (respectively).

Exhibit 8. Projects Studied Different Approaches to Construction of Models



Note: Categories are not mutually exclusive. *N* = 18.

In summary, in nearly all projects, students used models to explore scientific processes, and in half of the projects, students also constructed models using several different approaches.

Teacher Resources

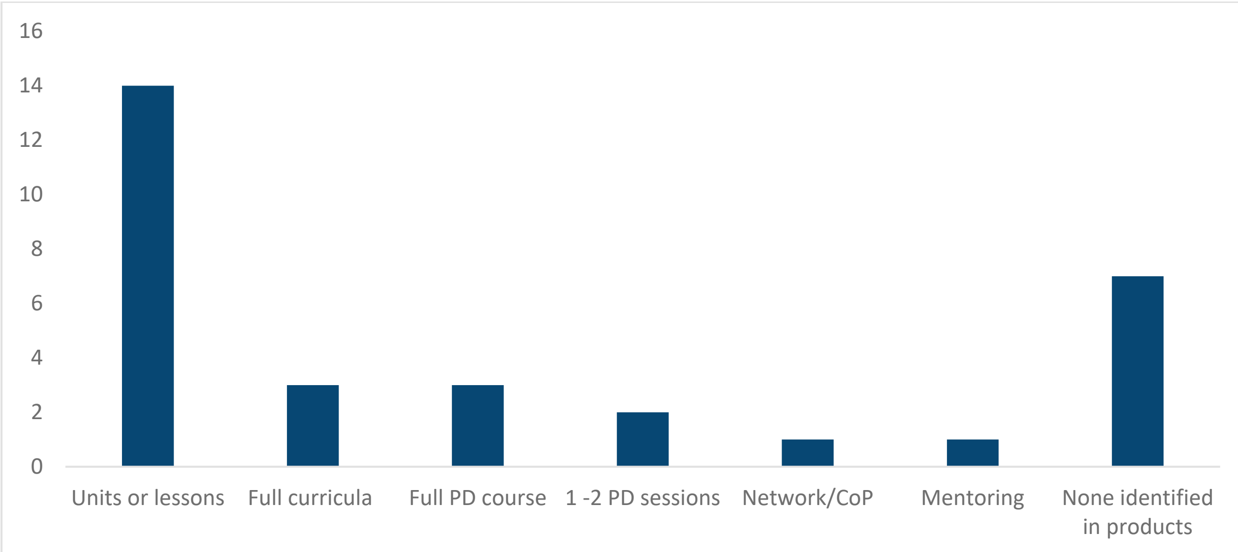
Projects developed several types of teacher resources, including lesson plans and professional development activities.

All of the projects developed or studied curriculum materials to varying extents. Typically, projects studied a supplemental unit or lesson, as was the case with 14 of 18 projects (Exhibit 9). The remaining four projects developed a full curriculum for a course (comprising multiple units).

Few projects offered professional development for modeling-based instruction. Three projects provided multiday professional development. One of these three also provided both a community of practice and mentoring. Two projects offered individual professional development sessions of a day or shorter in duration (Exhibit 9).[4]

[4] Based on personal communication with one principal investigator (Damelin, 2021), we understand that projects may have developed professional development materials and workshops to support implementation of the curriculum materials. These professional materials may not have been included in published articles.

Exhibit 9. Units or Lessons Were the Most Frequent Type of Professional Resource



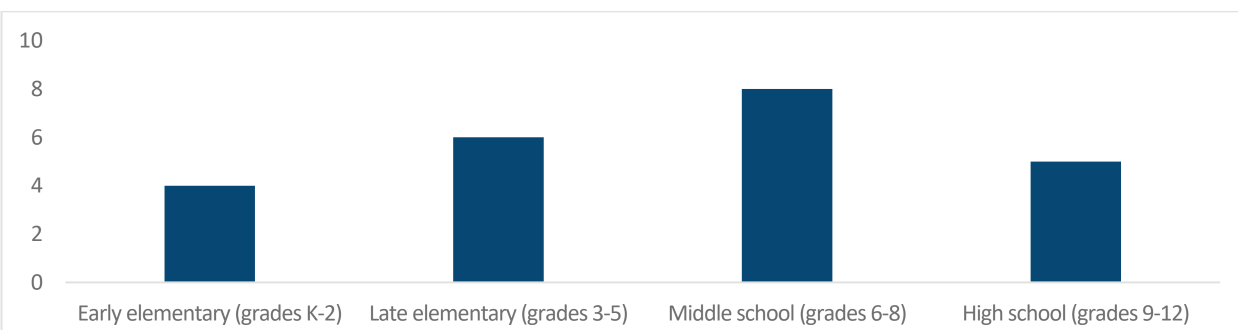
Note: CoP is community of practice; PD is professional development. Categories are not mutually exclusive. *N* = 18.

Teaching Context

Projects varied with respect to the teaching context, namely, the grade level and subject areas that they studied.

All grade levels were represented among the set of projects. Projects most frequently addressed the middle school grades (eight of 18 projects), with four to six projects addressing the remaining grade levels (Exhibit 10).

Exhibit 10. Projects Most Frequently Studied Modeling Resources in Middle School Settings

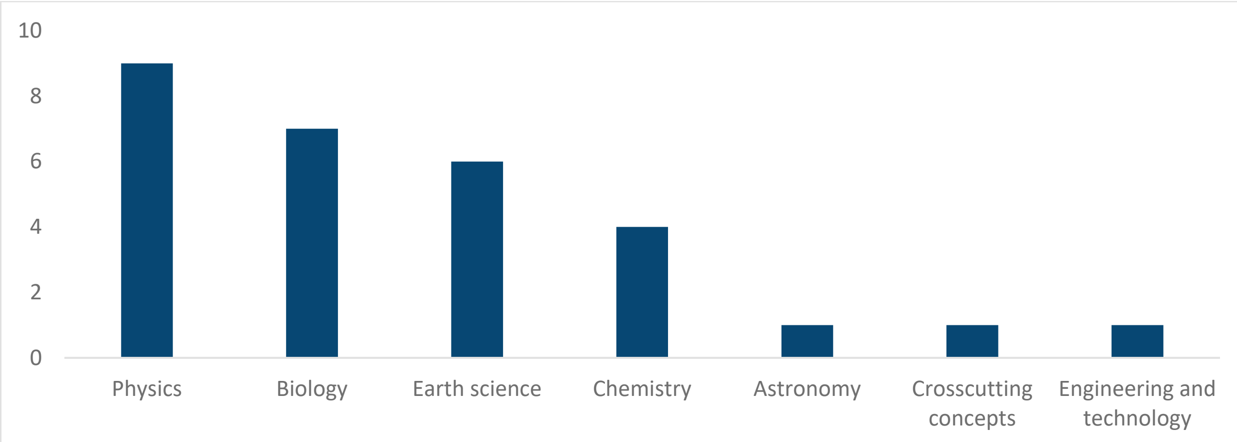


Note: Categories are not mutually exclusive. *N* = 18.

Physics was the most frequent content area. The frequencies of science content areas differed considerably (Exhibit 11). Half of the projects (nine of 18) addressed physics content, and nearly

40% (seven of 18) addressed biology. Only one project addressed astronomy or engineering/technology (respectively).

Exhibit 11. Projects Most Frequently Studied Modeling Resources Related to Physics



Note: Categories are not mutually exclusive. *N* = 18.

What research methods did projects use to study modeling?

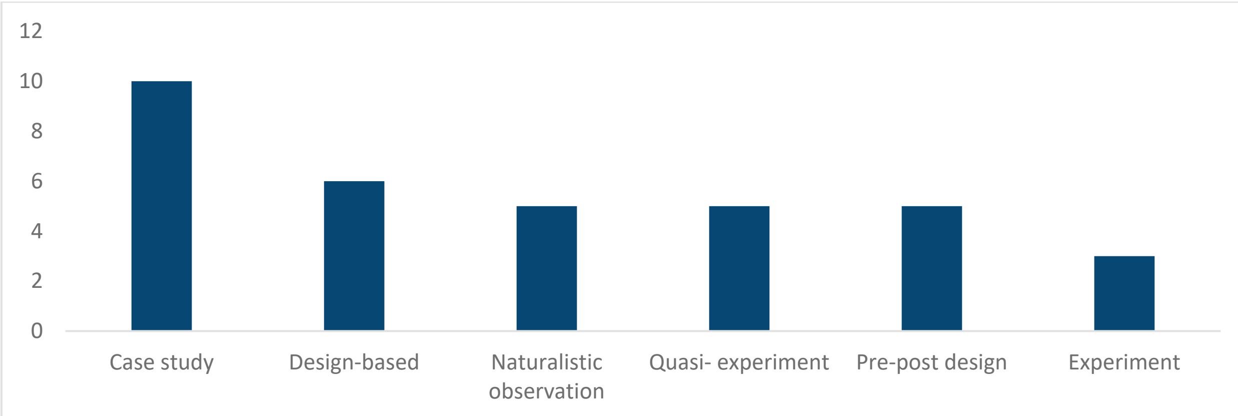
This section describes the research methods that projects used to study modeling interventions and resources. The 18 projects in this review each comprised multiple studies and methods. In this section we summarize the research designs that these projects employed, the types of student and teacher outcomes they measured, and their approach to measuring these outcomes.

Projects frequently used descriptive designs and less frequently used comparison groups.

Most projects used descriptive designs—case studies or naturalistic observation—to understand how students and teachers are using modeling resources (Exhibit 12).[5] These designs are a useful step in the research process for developing and testing these resources. A minority of projects used pre-/post-designs without a comparison group, and a minority used comparative designs that provide preliminary evidence of effectiveness.

[5] We combined case study and naturalistic observation designs into a single category based on the shared feature of being a descriptive rather than a comparative design.

Exhibit 12. Descriptive Designs, Such as Case Study or Naturalistic Observation, Were Used by Most Projects



Note: Design categories are not mutually exclusive. *N* = 18.

A majority of projects used descriptive designs. Twelve of 18 projects used a case study design (10 projects) or a naturalistic observation design (five projects), or both. The typical purpose of these types of designs was to understand how students and teachers interact with and use modeling resources (although one case study examined how different classroom structures affected the use of simulations). For example, one project used a multiple-case study design to study how six 3rd-grade teachers conceptualize modeling and how this relates to their implementation of a unit on the water cycle (Vo et al., 2015). Another type of descriptive design, used in six of 18 projects, was design-based research intended to inform the development of a particular aspect of a student resource. For example, one project sought to optimize a bee simulation game using four design cycles. Following each cycle, researchers used classroom observations and discussions with teachers to make refinements that would optimize game play and learning objectives (Peppler et al., 2018). Taken together, the prevalence of descriptive designs indicates that most of these projects were undertaking the development and refinement of a resource for modeling, rather than testing the effectiveness of a resource.

A minority of projects used a comparison group, typically with a small number of participants. Eight of 18 projects included an experimental or quasi-experimental study with a comparison group.[6] In six of these eight projects, the research design used groups comprising a single classroom each or a small number of students within a single classroom. For example, one project studied the instructional approach of bifocal modeling (described in Spotlight 1) by recruiting two classrooms of the same teacher. Students in one classroom participated in bifocal modeling, whereas students in the comparison classroom engaged in a group discussion and completed an activity sheet (Fuhrmann & Blikstein, 2017). Across these eight studies, the

[6] One project included studies with both types of designs.

average number of student participants was 100, and the average number of clusters (across all conditions) was fewer than four.

A minority of studies used pre-/post-designs. Five of 18 projects included a study using a pre-/post-design without a comparison group to examine program outcomes. For example, one project studied an instructional approach for incorporating playground-type “dramatic play” with a virtual reality simulation (Enyedy et al., 2017).

In summary, projects most typically used descriptive designs that provide insight into how students and teachers use modeling resources. A minority of projects used comparison groups, typically involving two or three classrooms. The use of a single classroom per condition is an example of a *single-unit confound.* The design of these studies is useful for program design and development, and establishes whether modeling interventions are achieving their intended outcomes on student modeling and science learning.

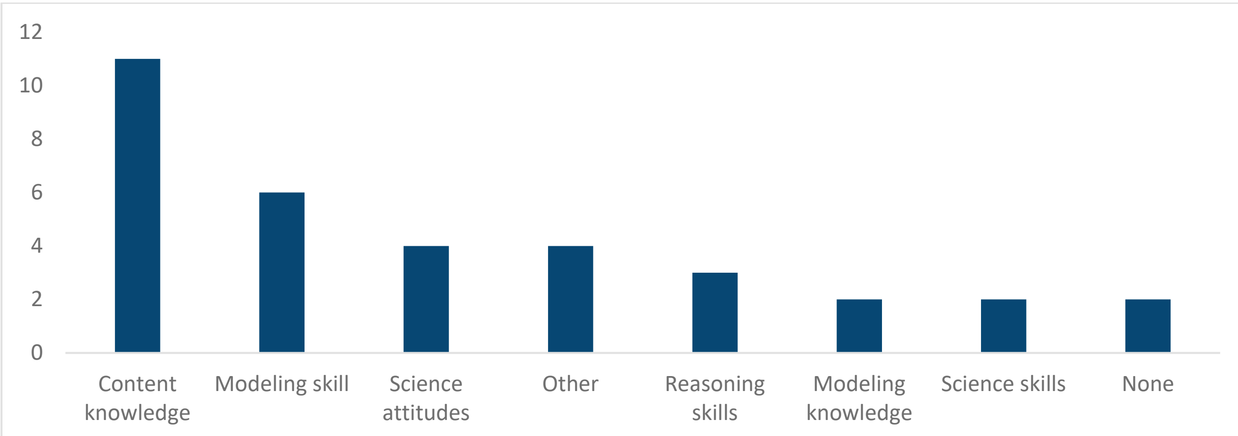
Most projects measured student outcomes; few measured teacher outcomes.

Nearly all projects (16 of 18) measured some type of student outcome, with a majority of projects (11 of 18) measuring students’ disciplinary content knowledge with paper-and-pencil assessments (Exhibit 13). One third of projects measured students’ modeling practice, typically by content-coding the models that students constructed. The four most common types of outcomes measured were science content knowledge, modeling practice, science-related attitudes, and scientific process skills, as described below.

- Eleven of 18 projects measured students’ science content knowledge, and, in every case, these projects used paper-and-pencil assessments to collect the data. For example, Peppler and colleagues (2020) created a 20-item multiple-choice test to measure student understanding of bee behavior.
- Six of 18 projects measured student modeling skill. In four of six projects, researchers coded student work products to construct a measure of model quality. For example, Baumfalk and colleagues (2018) coded models with respect to their “epistemic features,” such as model components, sequences, and explanatory processes. One project addressed student modeling practice based on verbal contributions coded using video observation (Williams & Clement, 2017). A final project used log files from the CTSiM system to construct metrics of model evolution and integration of conceptual and computational representations (Basu et al., 2016).
- Four of 18 projects measured students’ science-related attitudes. Three projects collected these data using surveys of science identity and interest, engagement in science class, and level of interest in specific topics covered by the unit (respectively). One project analyzed classroom videos to make judgments of the level of positive affect and excitement of students (Enyedy et al., 2017).

- Three of 18 projects measured students' science process skills (one of the dimensions of the NGSS). These projects addressed skills such as computational thinking (Basu et al., 2017), experimentation skills (Dede et al., 2017), and causal explanations (Grotzer et al., 2016).

Exhibit 13. A Majority of Projects Measured Students' Disciplinary Content Knowledge

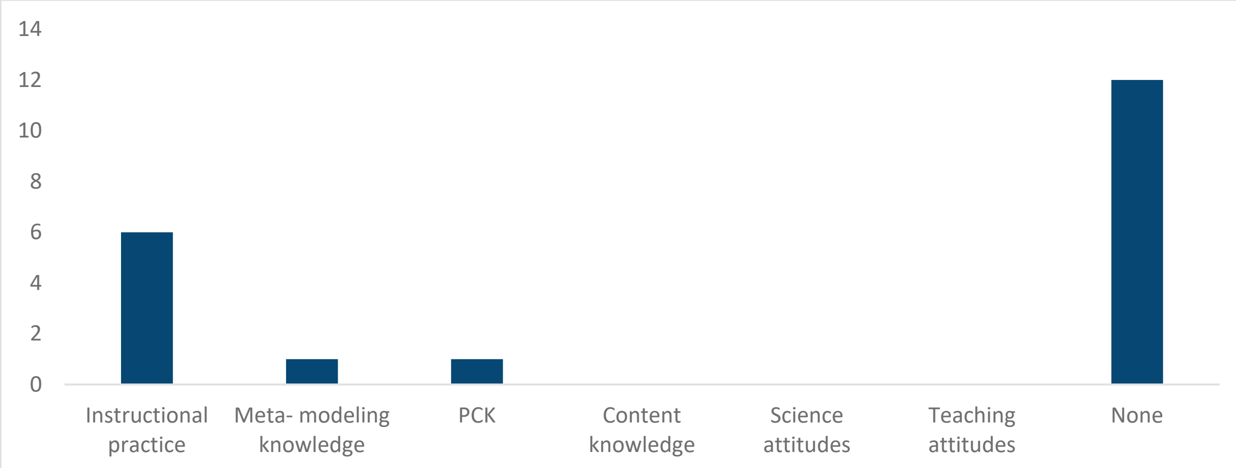


Note: Categories are not mutually exclusive.

One third of projects measured teacher outcomes. In comparison to student outcomes, relatively few projects (six of 18) measured teacher outcomes (Exhibit 14). The teacher outcomes measured by these projects include the following:

- Six of 18 projects included measures of teacher instructional practices related to modeling. In most cases (five projects), these measures were derived from observations or field notes. For example, Enyedy and colleagues' (2017) study of the implementation of a virtual reality simulation used analysis of a video case, coding for social processes and teacher scaffolding. Another project used a student survey of classroom science activities to derive an index score for inquiry instruction (McGee et al., 2017).
- Only one project included any teacher outcome other than instructional practice: Vo et al. (2015) coded observation and interview data for teacher meta-modeling knowledge and pedagogical reasoning (as well as for instructional practice).
- No projects measured teacher attitudes toward science or science teaching or teachers' disciplinary content knowledge.

Exhibit 14. A Minority of Projects Measured Any Type of Teacher Outcome



Note: Categories are not mutually exclusive. PCK is pedagogical content knowledge.

In summary, most projects (16 of 18) measured outcomes for students who use modeling resources. Projects frequently measured science content knowledge using paper-and-pencil tests. A minority of projects measured student modeling practice, typically by coding artifacts of modeling. Relatively few projects (six of 18) measured teacher instructional practices.

Project Spotlight 1: Assessing Model Quality

Bifocal Modeling: A New Framework for the Learning of Advanced STEM Content in Schools (NSF award #1055130; funded amount = $628,883)

Why spotlight this project?

Bifocal Modeling (Blikstein et al., 2012) is an inquiry-driven science learning approach that challenges students to design, compare, and examine the relationships between physical experiments and computational models (thus, "bifocal"). Students conduct physical experiments, construct models based on those experiments, and compare the data from both models in real-time. We highlight this project because its researchers developed and tested a rubric to assess model quality.

What was studied?

This project developed and tested the Bifocal Modeling approach at both the high school and upper elementary levels (Grades 5–11), and introduced a measure of modeling based on student drawings of models. Researchers examined different implementation modes of the Bifocal Modeling approach in a "typical" science classroom, within units about diffusion, bacterial growth, and osmosis. The project examined variations in the materials and technologies that students used to construct models, and measured model quality using a rubric (Exhibit 15). Researchers measured two dimensions of understanding: scientific content and meta-modeling knowledge.

Exhibit 15. Rubric for Rating Model Quality (in the "Naked Egg" Experiment Within the Osmosis Unit) (Fuhrmann & Blikstein, 2018)

Category	Description	Score
Macro and micro levels	Examines whether the model represents both micro and macro levels of the phenomenon.	No picture (0); general macroscopic picture of the experiment (1); drawing includes some or all of the particles, focusing on the molecular level with detail (2)
Temporal chaining	Explores whether students draw their model as a process or a static state.	No temporal chaining, just a static stage (0); some relationship with time or the idea of a "process" with steps (1)
Scientific explanation	Looks for formal scientific explanation of the phenomenon, including the variables participating in osmosis and their interaction with each other.	No explanation (0); an incomplete explanation in which students mention only a single factor and may have used concepts imprecisely (1); a more elaborated scientific explanation, including several sentences, and correct use of all main chemical concepts (2)
Communication	Examines whether the design of the model is communicative/clear to others.	No label or text near the drawing (0); students add word/words or arrows to the drawing; (1) students describe the movement of particles in a sentence or paragraph, and add arrows and labels to their drawings (2)

What was found?

Findings indicate that students engaging in a Bifocal Modeling activity designed detailed models that included scientific explanations. However, only students engaged in the model design component completed a rich, detailed model displaying molecular interaction at the micro level and developed a critical perspective about scientific models. Students in the Bifocal Modeling condition increased their content knowledge of osmosis and developed a meta-modeling understanding.

What knowledge did projects generate about how to support student modeling?

The 18 projects reported findings about three broad categories of supports for student modeling: teacher scaffolding, scaffolds embedded in digital tools, and technological enhancements to the perceptual experience of simulations. Overall, these projects added to the literature on the ways that teacher scaffolding and embedded scaffolds promote student engagement in modeling and the quality of models produced. Relatively few projects examined how to improve modeling-based instruction. Several projects reported technological enhancements, but few demonstrated how these enhancements affected student use of simulations.

Teacher scaffolding supported model construction and use.

As reviewed above, past research has demonstrated the importance of teacher scaffolding for enabling students to construct a model and use simulations. Among the 18 projects, seven projects included products that reported findings about teacher scaffolding. These findings fell into two broad categories: (1) how teacher scaffolding promotes student modeling or use of modeling platforms (addressed by five projects), and (2) how teacher scaffolding supported the use of digital simulations (two projects). Findings related to the former category include the following:

- Two projects produced case studies showing the importance of teacher scaffolding. Teachers' instructional moves, such as questions, requests for predictions, and prompts to check for model completeness, supported students through all steps of a structured modeling process (Palincsar et al., 2018; Williams & Clement, 2017; Williams et al., 2016).
- One project produced a correlational study of teachers who implemented a modeling-enhanced curriculum. Teachers who increased their supports for the articulation of model components and for explanatory processes of models had students who demonstrated improvement in the quality of models (Zangori et al., 2017; see Spotlight 2).
- In a naturalistic observation study, teacher scaffolding during one-on-one instructional sessions with students decreased the number of challenges that students encountered during a series of computational modeling activities (Basu et al., 2016). As part of this study, researchers developed the scaffolds they embedded in the CTSiM digital modeling resource (see Spotlight 4).
- In two projects, case studies found that teachers supported student use of digital modeling platforms. Teacher mediation and student discussion amplified the use of scaffolds embedded within the digital curriculum resources (Bielik et al., 2018; Palincsar et al., 2018).

Two projects generated products that reported how teachers scaffold the use of simulations. Specific findings include the following:

- A naturalistic observation study found that teachers helped students to attend to the key features of a computer simulation and understand their implications. For example, teacher facilitation of whole-group discussion of simulation software provided more opportunities for "recognizing and interpreting the meaning of visual features" in a simulation than did small-group discussions, despite the fact that the latter approach provided greater hands-on use of the software (Stephens & Clement, 2015a, p. 4).
- A naturalistic observation study found that among students using a computer simulation of molecules (in which students manipulated the movement of molecules through their own

physical movement), teachers encouraged students to reflect on the "rules" that determined states of matter. This supported students in revising these rules (Enyedy et al., 2017).

Exhibit 16 summarizes the products of the seven projects with respect to their major findings about teacher scaffolding.

Exhibit 16. Findings About Teacher Scaffolding of Modeling, by Study Design Type

Finding	Products With Descriptive Studies	Products With Correlational Studies
Teacher instructional moves support modeling.	Palincsar et al., 2018 Williams & Clement, 2017† Williams et al., 2016†	Zangori et al., 2017
Scaffolds for specific modeling tasks decrease student challenges.	Basu et al., 2016	
Teacher mediation and student discussion enhance use of digital modeling resources.	Bielik et al., 2018 Palincsar et al., 2018	
Scaffolding enhances use of computer simulations.	Enyedy et al., 2017 Stephens & Clement, 2015a	

†Products are from the same project.

In addition, one of these seven projects generated a quasi-experimental study of an intervention to enhance teacher support for modeling. This study found that the six teachers who received a weeklong training and then used a modeling-enhanced curriculum implemented more modeling-centered practices than the five teachers in a comparison condition (Baumfalk et al., 2018). None of the other 18 projects examined how a professional resource influenced teacher practice, either using a pre-/post-design or comparison group.

In summary, these seven projects highlight the role of teachers in supporting students' construction and use of models. Six of the seven projects we reviewed used a descriptive or pre-/post-design to identify types of practices or note apparent relationships. Given that only one of the 18 projects examined how professional resources affected instructional practice, an area for future research would be to develop and test professional resources for modeling-based instruction.

Project Spotlight 2: Promoting Teacher Instruction of Modeling

Project #1220675; Modeling Hydrologic Systems in Elementary Science (MoHSES); funded amount: $448,491.

Why spotlight this project?

The project focused on promoting teacher instruction of modeling and incorporating modeling-based instruction into existing curriculum materials. The project created a modeling-enhanced version of a 6-week FOSS [Full Option Science System] water unit by providing students with "opportunities to construct, use, evaluate, revise, and/or elaborate models of natural phenomena." The project provided teachers with a weeklong professional development course on modeling instruction. We spotlight this project because it was the only one to study the outcome of support for modeling instruction.

What was studied?

Researchers conducted an exploratory case study to describe how third-grade teachers understand different epistemic ideas of models and emphasize these ideas in their teaching (Vo et al., 2015; Zangori et al., 2017). In subsequent studies, researchers compared a modeling-enhanced version of a FOSS water unit with the nonenhanced version of the unit, measuring model-centered instructional practices of the teacher and the quality of students' model-based explanations (Forbes et al., 2015). Researchers measured the presence of five core epistemic features in student models (Exhibit 17) using a learning performance continuum for third-grade students' modeling-based explanations about groundwater.

Exhibit 17. Core Epistemic Features of Student Models

Core Epistemic Feature	Definition
Components	Elements of the system that students choose to illustrate
Sequences	Relationships that students articulate between various components
Explanatory process	Connections that students articulate between cause and effect for system processes
Mapping	How students understand and relate their representation to the physical world
Scientific principle	Connections that students make to underlying theory

Source: Zangori et al. (2017)

What was found?

Teachers who understood the importance of grounding models in evidence and showing cause-and-effect relationships provided more support for students to include these features.

The modeling-enhanced curriculum was associated with more model-centered instructional practices—particularly in relation to evaluating and revising models.

Early evidence suggests that certain instructional practices, such as emphasizing the components of groundwater and causal explanations for the water cycle, were associated with greater student improvement in model-based explanations.

Students who participated in the model-enhanced curriculum demonstrated more core epistemic features in their models than students in the comparison condition.

Embedded scaffolds supported modeling with feedback and guidance.

Eight projects provided evidence that scaffolds embedded in digital resources or curriculum materials supported students' modeling outcomes (as summarized in Exhibit 18). Three of these eight projects demonstrated that embedded guidance supports student use of computer simulations. Specific findings include the following:

- One project provided students with a guided process for studying a simulation of a pond ecosystem called EcoMUVE. Seventh- and eighth-grade students used probes to explore the pond and the surrounding area, and collected water, weather, and population data. The simulations included several scaffolds, such as step-by-step instructions for the use of probes and feedback on student measurements. These scaffolds were designed to help students "recognize the importance of pursuing non-obvious causes" (Grotzer et al., 2016, p. 6). The studies reviewed for this project did not report how these scaffolds enhanced the use of the simulation itself.[7]
- The EcoXPT version of this simulation included probes for measuring environmental variables; the scaffolds consisted of instructions for using the probes (Dede et al., 2017). In a pre-/post-design study, these scaffolds supported student experimentation using digital tools, with seventh-grade students demonstrating more sophisticated strategies for experimentation over time (Dede et al., 2017).
- Another project examined computer simulations in which students use their own gestures to manipulate quantitative functions, such as the amplitude of a wave. The simulated phenomena are measured with scales that exhibit exponential or logarithmic change. The simulations included embedded prompts for undergraduate students to reflect on different aspects of these phenomena (e.g., quantitative relationships between variables; Lindgren et al., 2019). Most students demonstrated greater content knowledge about earthquakes and gave more sophisticated causal explanations. The study did not report how these scaffolds enhanced the use of the simulation itself.

Four projects demonstrated how scaffolds embedded in curriculum materials help guide students through the modeling cycle. Some projects demonstrated that these scaffolded materials promoted student modeling outcomes. Specific findings include the following:

- The SageModeler platform provides an interface for model construction that prompts students to specify relationships among variables (e.g., pH and water quality) in semiquantitative terms (see Spotlight 3). Seventh-grade students using SageModeler were able to construct complex models and subsequently revise them by adding variables and relationships among variables (Bielik et al., 2018). These students demonstrated an

[7] Findings related to student outcomes for scientific knowledge and skills are discussed in the next section.

improvement in metamodeling knowledge (i.e., understanding of the purpose of models) on pre-/post-measures.

- A suite of applications provided several types of scaffolds, including just-in-time information, procedural supports, prompts to reflect on and discuss models, and multiple means of representation (e.g., drawing, writing, discussion). A case study described how teacher mediation and student discussion supported the use of these tools by sixth-grade students. This study did not report how the platform influenced student modeling behavior (Palincsar et al., 2018).
- A nondigital curriculum directed students to draw a model of the water cycle and consider cause, effect, and underlying mechanisms in their model. The curriculum activities prompted students to evaluate, discuss, and revise their models. Third-grade students receiving this curriculum demonstrated greater improvement in model quality relative to a comparison group, as measured by rubric-based ratings of each model's "epistemic features" (Baumfalk et al., 2018; Zangori et al., 2017; see Spotlight 2).
- The bifocal modeling instructional strategy directed students to compare data from a computer model with real-world data they collected. The classroom activity instructed students to create a paper-and-pencil model for osmosis and to animate particles with arrows and textual explanations. In a randomized experiment with one classroom per condition, ninth-grade students in the bifocal modeling condition demonstrated a greater understanding of modeling, as measured by ratings of four aspects of model quality (Fuhrmann & Bilkstein, 2017).

Two projects examined how feedback embedded in digital modeling tools promotes modeling construction and use.

- One project studied the scaffolds embedded in CTSiM, an agent-based visual programming and modeling platform (see Spotlight 4). The system provided textual feedback to students designed to highlight problems in students' models and suggest strategies for overcoming their difficulties. In two pre-/post-studies, sixth-grade students demonstrated better performance on conceptual and computational modeling tasks—measured by distance from ideal model specifications (Basu et al., 2017; Basu et al., 2016).
- Another project tested a building design simulator called Energy3D that enabled students to test ways to increase the energy efficiency of a building. The software provided feedback on middle-school students' design choices (Magana et al., 2019). This study did not report how this feedback influenced students' designs but noted that students struggled with graph interpretation. The authors concluded that further development of scaffolds was needed.

In summary, embedded scaffolds helped students represent relationships among variables and evaluate models relative to other data. Some projects provided detailed case studies of student use of the scaffolds, whereas others demonstrated the impact of the scaffolds on the modeling process relative to a comparison group. Students used the embedded scaffolds as intended, in digital simulations, model construction platforms, and nondigital curriculum materials. Some of these studies reported that students who used digital platforms and nondigital curriculum materials demonstrated improvement in the quality of their scientific models.

Exhibit 18. Findings About Embedded Scaffolds and Supports, by Study Design Type

Finding	Products With Descriptive Studies	Products With Comparison Studies
Scaffolds embedded in computer simulations support their use.	Grotzer et al., 2016 Dede et al., 2017	Lindgren et al., 2019*
Scaffolds embedded in curriculum materials guide students through the modeling cycle.	Bielik et al., 2018 Palincsar et al., 2018	Baumfalk et al., 2018[†] Zangori et al., 2017[†]
Embedded feedback may promote model construction.	Basu et al., 2017[†] Basu et al., 2016[†]	Magana et al., 2019*
Enhancing the perceptual experience of simulations increases their benefits.	Tomlinson et al., 2019**	Chen et al., 2014 Lindgren et al., 2019* Peppler et al., 2020

*Observed pre-/post-gains, but differences between groups were not significant.

**Product described perceptual enhancement but did not report its outcomes.

[†]Products in this cell are from the same project.

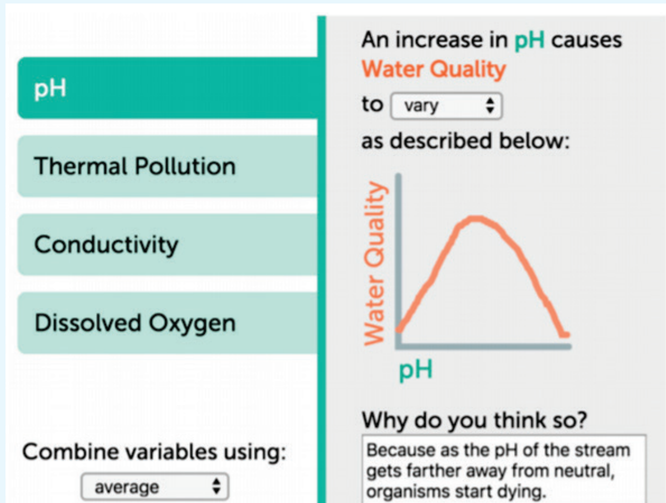
Spotlight 3: Digital Modeling Tool With Embedded Scaffolds

Collaborative Research: Supporting Secondary Students in Building External Models (NSF award #1417809)

Why spotlight this project?

SageModeler is a curriculum tool that supports students in implementing the process of constructing, using, evaluating, and revising models. The digital tool includes scaffolds for model construction by prompting students to specify relationships among variables in semiquantitative terms (Exhibit 19). We highlight this project because it measured student growth in modeling skill over time.

Exhibit 19. SageModeler Interface for Semiquantitative Specification of Relationships Between the Variables' pH and Water Quality



Source: Bielik et al. (2018)

What was studied?

This project examined how the digital resource and teacher instruction facilitated student modeling. Researchers used a design-based research approach to study student participation in modeling cycles, development of student models and meta-modeling knowledge, and changes in science-related attitudes when using the SageModeler tool in a water quality unit.

What was found?

Integrating SageModeler into the water quality unit enabled students to engage in all of the elements of modeling practice. Students participated in several modeling cycles.

Students improved their model accuracy and quality over the course of the unit. Students faced challenges in revising their models as they tended to add to their models rather than revise them.

Student understanding of models showed modest growth. Initially, students understood models as a visualization of a phenomenon. Some students explained that models can be used to understand relations among variables.

Students who participated in lessons with SageModeler demonstrated increased interest in the topics addressed by the water quality unit.

Technological affordances enhanced the perceptual experience of simulations.

Four projects studied technological affordances intended to enhance the perceptual experience of simulations (as summarized in Exhibit 20). Two of these projects reported findings indicating that these affordances enhanced the benefit of the simulations.

- One project used a haptic force feedback controller to enhance a digital simulation of buoyancy. The haptic force feedback provided students with a direct feeling of buoyancy forces in an interactive simulation. Third- and fifth-grade students who received this feedback spent more time using the digital simulation, and demonstrated fewer misconceptions, than a comparison group of students that used the simulation without the haptic force feedback. The study did not include inferential statistics to test this difference (Chen et al., 2014).
- In a second project, first-grade students used radio frequency identification (RFID)-equipped bee puppets to simulate the food gathering behaviors of bees (pictured in Exhibit 21). The project tested the effect of enhancing these puppets with indoor positioning technology, which afforded a third-person view of the interaction of agents (in addition to the first-person experience of being an agent). Students in one classroom who received the third-person view demonstrated a greater understanding of system-level concepts compared with students in another classroom who had only a first-person, agent-level view (Peppler et al., 2020). This result suggests that providing a third-person view of agents promotes understanding of the system.

Two additional projects examined perceptual enhancements to simulations but did not report direct evidence of the benefit of these enhancements.

- One project studied simulations in which undergraduate students used hand gestures to define quantitative functions, such as multiplication or exponential growth (Lindgren et al., 2019). The study did not provide a direct measure of how these hand gestures enhanced students' perceptual experience, but students demonstrated improved content knowledge and causal explanations on pre-/post-tests.
- Finally, a fourth project conducted design-based research on the integration of visual, sound, and textual features into a physics simulation (Tomlinson et al., 2019). Participants in the study were adults with visual impairments, children, and college students. The participants typically reported high overall usability of the simulation and made relevant interpretations of the added perceptual elements. The study did not examine how these elements influenced participants' interactions with the simulation.

Exhibit 20. Findings About Embedded Scaffolds and Supports, by Study Design Type

Finding	Products With Descriptive Studies	Products With Comparison Studies
Study reported findings of the usability of perceptual enhancements to a simulation.	Tomlinson et al., 2019**	
Enhancing the perceptual experience of simulations increases comprehension.		Chen et al., 2014 Lindgren et al., 2019* Peppler et al., 2020

*Observed pre-/post-gains, but differences between groups were not significant.

Exhibit 21. Student Uses BioSim's Radio Frequency Identification-Equipped Bee Puppets to Simulate Food-Gathering Behaviors of Bees

Source: National Science Foundation Award Abstract #1324047. Available at https://www.nsf.gov/awardsearch/showAward?AWD_ID=1324047#0.

What knowledge did projects generate about the relationship between modeling and scientific knowledge, skills, and attitudes?

The projects in this review generated some evidence about the relationship between modeling and science outcomes related to knowledge, skills, and attitudes. Eleven of the 18 projects used pre-/post-, quasi-experimental, or experimental designs to examine the increase in knowledge or skills following the use of these resources. The reported results suggest that student modeling is associated with an increase in scientific knowledge and skills, as indicated by pre- to post-test change. There was little evidence, however, that students who engaged in modeling had a greater increase in knowledge or skills relative to a comparison group that did not engage in modeling. In this section, we summarize findings about two broad categories of resources: simulation software and platforms supporting the development, testing, and revision of models.

Students demonstrated increased science knowledge and skills after using simulations.

Across seven projects, students who used computer simulations to explore scientific phenomena demonstrated an increase in scientific content knowledge or skill (see Exhibit 22 for a summary).[8]

- *Content knowledge.* Students demonstrated pre-/post-growth in scientific content knowledge following the use of a computer simulation (Chen et al., 2014; Enyedy et al., 2017; Dede et al., 2017; Lindgren et al., 2019; Magana et al., 2019). Two of these projects employed a comparison group; these included the projects testing the simulation in which students used their own gestures to modify the input variables (Lindgren et al., 2019), and the simulation that employed haptic feedback (Chen et al., 2014). Neither of these projects, however, found a significant difference in the amount of pre-/post-growth for students who used the simulation versus those who did not use the simulation.
- *Science-related skills.* Two other projects examined the science-related skills of causal explanations and systems thinking (respectively). In one project, first-grade students in a classroom participating in a digitally enhanced bee simulation demonstrated greater growth in systems thinking (as measured through a multiple-choice test) than students in a classroom that used the nonenhanced version (Peppler et al., 2020). In a second project, seventh- and eighth-grade students who used the scaffolds embedded in EcoMUVE did not

[8] This group of projects excludes the four projects in the next section that tested a resource that allowed students both to construct models and use computer simulations.

show a more sophisticated understanding of the causal dynamics in the virtual ecosystem than a comparison group (Grotzer et al., 2016).

Exhibit 22. Products Examining the Relationship Between Use of Simulations and Science Knowledge or Skill

Finding	Products With Descriptive Studies	Products With Comparison Studies
Students showed gains in content knowledge after using simulations.	Enyedy et al., 2017 Dede et al., 2017	Chen, 2014* Lindgren et al., 2019* Magana et al., 2019*
Students showed gains in scientific skills after using simulations.		Peppler et al., 2020 Grotzer et al., 2016*

*Observed pre-/post-gains, but differences between groups were not significant.

Constructing and testing models improved student science learning and attitudes.

Four projects reported initial evidence that resources to support modeling improved students' learning of science content or attitudes toward science learning (Exhibit 23).

- Ninth-grade students in one classroom constructed a model and then evaluated it using data collected from a physical experiment and a simulation. These students had greater gains in content knowledge (assessed with a multiple-choice test) than a second classroom serving as a comparison group (Fuhrmann & Bilkstein, 2017; also see Spotlight 1).
- Sixth-grade students who used a version of the CTSiM modeling platform with adaptive scaffolding demonstrated stronger improvement in both scientific knowledge and computational thinking skills than a comparison group that used CTSiM without the adaptive scaffolding (Basu et al., 2017; also see Basu et al., 2016). The two groups were all students of the same teacher.
- A field test of the Interactions curriculum, which includes a suite of computer simulations and other modeling supports, found a positive association between levels of inquiry instruction and pre-/post-changes among high school students in content knowledge and attitudes toward the focus of the curriculum (McGee et al., 2017).[9]

[9] The study measured inquiry instruction with student survey ratings of the frequency of seven different inquiry practices, one of which was modeling.

- Seventh-grade students who used SageModeler to construct and test models related to water quality (e.g., pH and water quality) expressed greater interest in that topic on pre-/post-surveys (Bielik et al., 2018, see Spotlight 3).

Exhibit 23. Products Examining the Relationship Between Constructing Models and Science Knowledge or Skill

Finding	Products With Descriptive Studies	Products With Comparison Studies
Students who compared conceptual models with simulated data had increased content knowledge.	McGee et al., 2017	Fuhrmann & Bilkstein, 2017
Students who constructed models had greater interest in the topic.	Bielik et al., 2018	
Adaptive scaffolding in modeling promotes scientific knowledge and computational thinking skills.		Basu et al., 2017

In summary, the 18 projects in this review generated new knowledge about the relationship between modeling and science-related outcomes. Among projects studying student use of computer simulations, seven projects demonstrated pre-/post-changes in content knowledge or science-related skills. Among projects studying student use of curricular resources for constructing models, four demonstrated pre-/post-improvements in content knowledge or science-related attitudes. Two of these projects demonstrated greater improvement in the treatment group relative to the comparison group, with each group comprised of a single classroom or teacher. These findings suggest a positive relationship between modeling resources and student outcomes. Future research could provide additional evidence for the impact of these resources on student content knowledge, science skills, and science-related attitudes, such as through the use of more rigorous impact designs.

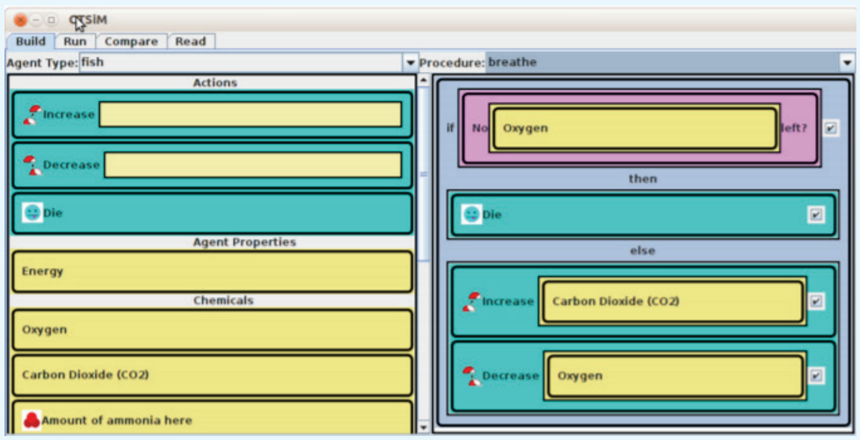
Spotlight 4: Support for Modeling and Science Learning

Extending CTSiM: An Adaptive Computational Thinking Environment for Learning Science Through Modeling and Simulation in Middle School Classrooms (NSF award #1441542; total funded amount: $1,348,142)

Why spotlight this project?

CTSiM is a modeling platform with which students can construct a conceptual model, create a computational model, and compare it with an expert simulation to learn about scientific topics and computational principles. For model construction, the interface provides a structure for selecting agents and their properties for specific scientific phenomena. The interface, depicted in Exhibit 24, links the conceptual to the computational model and indicates which relationships in the former are represented in the latter. CTSiM provides adaptive scaffolds, delivered as text-based dialogue with a "mentor agent," which help students identify problems with their models and suggest solutions. We highlight this project because it provides initial evidence that embedded scaffolds can enhance modeling and promote science learning.

Exhibit 24. CTSiM's Model Construction Interface



Source: Basu et al. (2017)

What was studied?

The goal of the project was to identify the types of challenges that students encounter and what strategies (i.e., scaffolds) teachers use to overcome them, and then incorporate those types of scaffolds into CTSiM. In one study, researchers analyzed classroom videos to identify the challenges that students encountered during modeling and ways that teachers scaffolded the task. In subsequent studies, researchers examined how adaptive scaffolds in CTSiM supported students when they faced challenges in modeling. These studies measured student learning of kinematics and biology concepts using log files to derive metrics of model evolution and integration of conceptual and computational representations.

What was found?

The adaptive scaffolding helped students to integrate and use the linked modeling representations (namely, the conceptual and computational models). The automated feedback improved the resulting modeling performance. Moreover, these additional scaffolds were associated with stronger gains in kinematics and ecology science content as well as computational thinking concepts and skills.

Finally, the project demonstrated that developing accurate models, improving them over time, and integrating different model representations are associated with stronger learning of science content.

Summary and Conclusions

Based on this review, we present conclusions about the focus of modeling research as well as major findings of this research. NSF awarded 18 DRK–12 grants from 2011 to 2015 to projects focusing on modeling-based learning. A major finding our review is that most of these projects focused on developing student resources, such as curriculum materials, modeling platforms, and computer simulations. Nearly every project studied student use of models to explore scientific phenomena, and, in most cases, these models were computer simulations. More than half of projects (10 of 18) focused on the use of these simulations as opposed to other components of the modeling cycle. Half of the projects (nine of 18) studied modeling construction, with most of these (seven of 18) addressing model testing and revision as well. In many cases, projects developed scaffolds to support students as they constructed models or used computer simulations. Corresponding to this focus, the projects primarily examined student outcomes—mostly disciplinary content knowledge—and, to a lesser extent, student modeling practice and skill.

In comparison to the focus on student resources and learning outcomes, relatively few projects focused on teacher supports or teacher outcomes. A minority of projects (five of 18) developed or tested professional development for modeling-based instruction, and only a single project measured the instructional outcomes of professional development. Among the six projects that measured teacher outcomes, they mainly focused on instructional practice rather than measures of knowledge of or beliefs about modeling. Because most projects developed and studied new resources for modeling, few projects studied general questions about modeling (i.e., unconnected to an intervention). Thus, there were few studies about how student modeling develops and how to promote teacher pedagogical skills related to modeling-based instruction. Given the apparent need for supporting teachers with modeling instruction, this may be an important area for future investment of the DRK-12 program.

It also should be noted that none of these projects focused on measuring program implementation.[10] Although a limited number of projects examined teacher practice, these projects did not operationally define what constitutes adequate or strong implementation and examine the factors that promote or inhibit implementation. To the extent that this is the case, NSF and other funders (as well as researchers) may consider whether this too may be a worthwhile area for investment.

The 18 projects produced new knowledge on how to support student modeling. A common theme among the findings was the importance of scaffolding student efforts at modeling. A group of seven projects highlighted the role of teacher scaffolding. Teacher instructional moves (e.g., questions, requests for predictions) supported construction and revision of models. Teacher facilitation also helped students to understand simulations and make use of scaffolds embedded in them. Eight projects highlighted the role of scaffolds embedded in digital resources or curriculum materials. These scaffolds included guided instructions for how to interact with a simulation and feedback or prompts to students guiding them to attend to certain aspects of the simulated environment. Embedded scaffolds also supported model construction and revision, such as by providing a step-by-step process for specifying the relationship among variables in a model. The findings supported the conclusion that scaffolds provided by teachers or embedded in materials are effective, as indicated by ratings of student model quality. Finally, a group of four projects studied technological affordances intended to enhance the perceptual experience of simulations (e.g., haptic force feedback) or visualization of data from simulations (e.g., charts of variables). Two of these projects reported findings that suggest these affordances enhanced the benefit of using the simulations.

The projects in this review generated initial evidence about the relationship between modeling and science outcomes related to knowledge, skills, and attitudes. Most projects used case studies, naturalistic observation, and design-based research to understand how students interact with specific modeling resources. The projects demonstrated that students who use simulations or modeling platforms show pre-/post-gains in their scientific content knowledge or attitudes toward science. Two projects provided evidence demonstrating greater improvement of a treatment group relative to a comparison group using small designs. Further research using larger and more rigorous designs would be necessary to provide moderate or strong evidence of the efficacy of these modeling resources.

[10] This point was suggested by both of this project's two external content experts. We had no formal code for whether a research product included a study of program implementation or scale-up; thus, this finding is not included in the previous sections of this report.

No project examined modeling-based instruction as an instructional approach independent of a specific resource. This may reflect that under DRK-12, NSF mainly funds the development of resources rather than research on instructional practices.

This review suggests several possible future directions for modeling research, including the following:

- ***Describe learning progressions for modeling.*** In the present review, a small number of projects described the change in student modeling over the course of a unit. Future research could identify how learning expectations of students could develop over the course of an entire year. Considering that most of the projects studied curriculum materials spanning a single unit, findings from such research could support development of a curriculum with greater scope.
- ***Develop assessments of student modeling skill.*** Several projects assessed the quality of student modeling as an outcome; these projects analyzed observations, log files, and paper-and-pencil artifacts. With further research and development, it may be possible to develop assessment resources that would be feasible for teachers. For example, modeling platforms could incorporate mathematical measures of modeling quality (such as correspondence to an ideal model) to provide objective feedback to students and teachers. A challenge would be to integrate these assessments of modeling with particular disciplinary core ideas or crosscutting concepts, as envisioned by the NGSS.
- ***Develop effective instructional practices to support modeling instruction***. One project examined how teacher beliefs and practices were related to student outcomes, but these studies were small in scope (Vo et al., 2015; Zangori et al., 2017). Further research would help determine the extent to which these findings can be extended. Similarly, few projects in this synthesis studied interventions focused on building teacher pedagogical knowledge and skill related to modeling. To the extent that teachers express low levels of confidence in their ability to teach this skill (Kang et al., 2018), research on effective professional development is a priority.
- ***Measure a wider scope of outcomes.*** Future projects could measure a wider range of teacher and student outcomes. Although 11 of 18 projects measured scientific knowledge, only six projects examined modeling skill, and four or fewer projects examined the outcomes of scientific reasoning, science process skills, meta-modeling knowledge, or attitudes toward science learning. Few projects examined teacher instructional practice, and only one examined the outcomes of pedagogical content knowledge or meta-modeling knowledge. These are outcomes that others have predicted for interventions to support model-based instruction (e.g., Haag & Megowan, 2015; Halloun, 2007; Schwarz et al., 2009); their measurement would enhance research on modeling resources and interventions.

- ***Generate more rigorous evidence for effectiveness.*** Many of the projects drew upon existing knowledge of modeling and simulations to develop modeling tools and resources. Some of these projects reported promising results of these resources that warrant further testing. A next step in the progression of knowledge about these resources would involve research designs that can provide evidence for effectiveness (see Earle et al., 2013, for further discussion of the types of research and progression of knowledge). There were three projects that used randomized experiments, but each of these was limited to a handful of classrooms. Recruiting a larger sample of teachers could provide more robust evidence for effectiveness and for the feasibility of implementation across classrooms and contexts.

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Appendix A. Data Collection and Analysis

Data collection and analysis began with searching and screening the literature to identify the products of each Discovery Research PreK-12 (DRK-12) project and screening them for relevance to the topical synthesis. The research team coded the relevant products with reference to the research questions.

Literature Search and Screening

The literature search yielded a corpus of publications and documents associated with the identified DRK-12 projects. We have conducted the initial step of a literature search. We gathered citations for publications and resources using six sources: Web of Science, ERIC, PsycINFO, Google Scholar, Research.gov, and the Community for Advancing Discovery Research in Education (CADRE; cadrek12.org) website. This search strategy targeted documents that either referenced the numeric award ID or had project leaders listed on the Research.gov or CADRE websites. We excluded from further consideration projects that only developed simulated classroom environments for teacher training.

Using the three literature databases (Web of Science, ERIC, and PsycINFO), we searched for the numeric award ID in the funding information search fields (e.g., the grant number field for Web of Science). Using Google Scholar, we searched for documents whose full text contained the numeric award ID and the term “NSF” or “National Science Foundation.” Google Scholar can complement searches of scientific databases by finding relevant gray literature sources (Haddaway et al., 2015). We conducted these searches using the full list of award IDs connected to the identified projects. For instance, a collaborative research project will have multiple award IDs, so we searched for documents containing any of those award IDs. To complement these award ID-based search methods, we developed web scrapers in the *rvest* package in R (Wickham, 2019) to automatically extract citations and other resources (e.g., links to project websites) from the project-specific pages on the Research.gov and CADRE websites. For Research.gov, this search included the public project outcome reports.

We merged search results from these six different sources using the *revtools* package in R (Westgate, 2018), which yielded 529 unique citations after removing duplicates. These citations indexed a diverse set of records and abstracts, including journal articles, conference presentations, book chapters, project websites, project outcome reports, videos on the CADRE website, and other miscellaneous records. From this pool of products, we identified 114 abstracts containing the term “simulation” or “model.” The research team screened these abstracts for relevance to the topical synthesis. Some of these projects did not explicitly focus on student modeling but nonetheless produced findings relevant to the topic, whereas several other projects featured student modeling as their central research goal. We prioritized documents that were publicly available, peer reviewed, and most likely to address the topics associated with our research questions. We recognize that these criteria exclude certain types of products, such as doctoral dissertations, but adopted this standard practice for research synthesis. For a manageable set of documents to review, we selected up to three documents per project to review and code. We removed documents from analysis if we could not find at least one produced document that was relevant to the topic. Finally, we invited principal investigators to review the set of identified documents and provide other publications or products associated with their grants that may meet our inclusion criteria. In total, our synthesis included 33 documents from 18 NSF projects (Appendix B).

Coding of Articles

The research team created a coding structure aligned with the study's six research questions (Appendix C) and applied this structure to the 33 documents. The lead author and another researcher jointly coded 17 of 33 articles, resolving coding discrepancies through discussion and subsequently clarifying definitions of coding categories. The two researchers each coded (respective) halves of the remaining 16 articles.

Appendix B. Summary of Projects

Project No.	Project Name	Modeling Resource	Products
#1055130	Bifocal Modeling: A New Framework for the Learning of Advanced STEM Content in High School	NetLogo: computer modeling platform	Bilkstein (2012) Bilkstein, Fuhrmann, & Salehi (2012) Fuhrmann & Bilkstein (2017) Fuhrmann, Bumbacher, & Bilkstein (2018)
#1118530	EcoMobile: Blended Real and Virtual Immersive Experiences for Learning Complex Causality and Ecosystems Science	EcoMUVE: augmented reality tool	Dede, Grotzer, Kamarainen, Metcalf, & Tutwiler (2012) Grotzer, Tutwiler, Kamarainen, Derbiszewska, Metcalf, & Dede (2016)
#1220675	Modeling Hydrologic Systems in Elementary Science (MoHSES)	FOSS Water Unit: modeling enhanced curriculum	Baumfalk, Bhattacharya, Vo, Forbes, Zangori, & Schwarz (2018) Vo, Forbes, Zangori, & Schwarz (2015) Zangori, Vo, Forbes, & Schwarz (2017)
#1222709	Identifying Science Teaching Strategies for Promoting Reasoned Discussions of Concepts and Simulations	PhET Simulation, Energy Skate Park	Stephens & Clement (2015a) Stephens & Clement (2015b)
#1232388	Developing and Testing a Model to Support Student Understanding of the Sub-Microscopic Interactions That Govern Biological and Chemical Processes	Interactions Curriculum: modeling enhanced curriculum	Mayer, Damelin, & Krajcik (2013) McGee, McGee-Tekula, & Duck (2017)
#1316473	ASPECT: Advancing Science Performance With Emerging Computer Technologies	Novint Falcon: simulation tool, force feedback controller	Chen, Borland, Russo, Grady, & Minogue (2014)
#1323767	DIP: The Science Through Technology Enhanced Play (STEP)	Science Through Technology Enhanced Play (STEP): simulation tool	Dahn, Enyedy, & Danish (2018) Enyedy, Danish, DeLiema, Saleh, Lee, Morris, & Illum (2017)

Project No.	Project Name	Modeling Resource	Products
#1324047	DIP: BioSim: Developing a Wearable Toolkit for Teaching Complex Science Through Embodied Play	BioSim: wearable simulation toolkit	Peppler, Thompson, Danish, Moczek, & Corrigan (2020) Peppler, Thompson, Danish, Moczek, & Han (2018)
#1345231	EAGER: WeInvestigate: Collaborative exploration of scientific phenomena with the assistance of hand-held simulations, prose, and graphics	"We" Curriculum: modeling software applications	Palinscar, Fitzgerald, Marcum, & Sherwood (2018)
#1416781	Learning and Ecosystems Science and Complex Causality Through Experimentation in a Virtual World	EcoXPT Simulation: virtual ecosystem	Dede, Grotzer, Kamarainen, & Metcalf (2017)
#1417722	Collaborative Research: Model My Watershed—Teaching Environmental Sustainability	Water filter earth model	Kilpatrick, Marcum-Dietrich, Wallace, & Staudt (2018)
#1417809	Collaborative Research: Supporting Secondary Students in Building External Models	SageModeler: modeling platform	Bielik, Opitz, & Novak (2018) Bielik, Damelin, & Krajcik (2019)
#1441542	DIP: Extending CTSiM: An Adaptive Computational Thinking Environment for Learning Science Through Modeling and Simulation in Middle School Classrooms	CTSiM: modeling platform	Basu, Biswas, & Kinnebrew (2016) Basu, Biswas, & Kinnebrew (2017) Basu, Biswas, Sengupta, Dickes, Kinnebrew, & Clark (2016)
#1441563	DIP: Developing Crosscutting Concepts in STEM With Simulation and Embodied Learning	ELASTIC3S: cyberlearning platform	Lindgren, Morphew, Kang, & Junokas (2019)
#1503196	Collaborative Research: SmartCAD: Guiding Engineering Design With Science Simulations	SmartCAD: simulation tool	Magana, Elluri, Dasgupta, Seah, Madamanchi, & Boutin (2019)
#1503439	Ramping Up Accessibility in STEM: Inclusively Designed Simulations for Diverse Learners	PhET: physics simulation tool	Tomlinson, Kaini, Harden, Walker, & Moore (2019)

Project No.	Project Name	Modeling Resource	Products
#1503456	Strategies for Leading Classroom Discussions Aimed at Core Ideas and Scientific Modeling Practices	OGEM: modeling process tool	Williams & Clement (2017) Williams, Oulton, & Taylor (2016)
#1522945	EXP: Promoting Learning Through Annotation of Embodiment (PLAE)	Science Through Technology Enhanced Play (STEP): simulation tool	Enyedy, Danish, Deliema, Saleh, Lee, Morris, & Illum (2017)

Appendix C. Coding Scheme for Research Articles

Coding Field	Response Options
1. What type of students and content areas were the focus of study?	
Grade Level	Early elementary (Grades K–2)
	Late elementary (Grades 3–5)
	Middle school (Grades 6–8)
	High school (Grades 9–12)
	Not reported/general K–12
Science Content	Physics
	Astronomy
	Chemistry
	Earth science
	Biology
	Other life sciences
	Engineering and technology
2. What professional development resources for modeling instruction were studied?	
Professional Development Products (adapted from CADRE, 2014)	Stand-alone instruction, manuals, guides, or other information
	One or two professional development sessions, classes, or meetings
	Full professional development course
	Full curricula for courses
	Supplemental units or lessons
	Networks or professional learning communities
	Supervision or mentoring
	None
3. What research methods were used to study modeling interventions and resources? What types of outcomes were measured?	
Study Design	Survey
	Quasi-experimental design (QED)
	Experimental (randomized controlled trial)
	Case study
	Naturalistic observation
	Other

Coding Field	Response Options
Data Source (adapted from D'Angelo et al., 2014)	Assessment (knowledge or skill)
	Surveys
	Log files
	Interviews
	Observation/Video analysis
	Student work products
	Other artifacts
	Other
Teacher Outcomes (adapted from CADRE, 2014)	Science-related attitudes/beliefs
	Teaching-related attitudes or beliefs
	Instructional practice
	Disciplinary content knowledge
	Meta-modeling knowledge
	Pedagogical content knowledge
	Other
	None
Student Outcomes (adapted from Halloun, 2007)	Science-related attitudes/beliefs
	Disciplinary content knowledge
	Meta-modeling knowledge
	Modeling practice and skill
	Scientific process skills other than modeling
	Reasoning skills, such as causal explanations
	Other
	None
4. What student modeling activities and resources were studied?	
Student Learning Supports (adapted from CADRE, 2014)	Computer, internet, or digital activities and resources
	Nondigital activities and resources
	Student assessments
	None
Modeling Resource Name	Free response
Digital Resource (adapted from D'Angelo et al., 2014)	Conceptual model creation software (e.g., SageModeler)
	Computational model creation software
	Virtual lab

Coding Field	Response Options
	Phenomenon simulation
	Virtual world
	Other simulation
	Other
	None
Student Simulation or Modeling Activity	Creating a model
	Using the model to make predictions
	Evaluating the model based on data; comparing simulated versus observed data
	Revising/improving the model (e.g., to increase its explanatory power)
	Explore phenomena or run simulations
	Other
	None
Student Representation of Conceptual Framework	Conceptual model illustrations, drawings, concept maps, and so on
	Computational models
	Scientific (textual or verbal) explanations of phenomena
	Mathematical models
	Physical models
	None
5. What new knowledge was produced about teaching and learning related to modeling?	
Research Topics Relevant to Teachers and Instruction	How do teachers' knowledge and instructional practice related to modeling develop? What influences this development?
	What are effective approaches to promote teachers' knowledge and instructional practice related to modeling?
	How do teachers understand the purpose of models—in science (meta-modeling knowledge) and in the learning of science?
	To what extent and in what ways do teachers support student modeling?
	To what extent and in what ways do teachers integrate modeling into disciplinary topics?
	Other

Coding Field	Response Options
	None
Research Topics Relevant to Student Learning	How do students' meta-modeling knowledge and modeling practice develop? What influences this development?
	What are effective instructional approaches and resources for supporting student modeling?
	What are effective scaffolds or supports for student use of simulations?
	To what extent and in what ways do students engage in modeling?
	What is the relationship between modeling-based learning and other scientific knowledge, skills, and attitudes?
	What is the relationship between simulation use and scientific knowledge, skills, and attitudes?
	Other
	None
6. What evidence was generated about the effectiveness of modeling and simulation interventions and resources?	
Impact of Professional Learning on Teacher Knowledge, Skills, and Practice	Science-related attitudes/beliefs
	Instructional practice
	Disciplinary content knowledge
	Meta-modeling knowledge
	Pedagogical content knowledge
	None
Impact of Instructional Methods and Resources on Student Knowledge, Skills, and Attitudes	Science-related attitudes/beliefs
	Disciplinary content knowledge
	Meta-modeling knowledge
	Modeling practice
	Scientific process skills other than modeling
	Reasoning skills, such as causal explanations
	None

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