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A Review of Teaching and Learning Sequences for the Scientific Practice of Modeling

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ABSTRACT

Modeling is widely recognized as a core scientific practice and an essential component of science learning. Although numerous teaching and learning sequences (TLSs) have been proposed to support modeling in science education, the field lacks both a comprehensive review and a shared understanding of their design features. This review addresses that gap by systematically identifying and analyzing 18 distinct modeling-focused TLSs proposed in peer-reviewed articles and book chapters (representing a 1987-2025 timespan), with a focus on points of convergence and divergence across the TLSs. While several common components and learning goals emerged, I highlight five key areas of divergence that raise critical considerations for the future development of modeling-based TLSs. Building on these findings, I propose a set of design and research considerations for scholars seeking to advance work in this domain. I conclude with a description of three future research agendas that aim to strengthen the theoretical and practical foundations of modeling-focused TLSs in science education.

Keywords: modeling, science education, teaching and learning sequences

Introduction

Scientists use models to help explain the natural world (Gilbert & Boulter, 2000; Gilbert & Justi, 2016; Greca & Moreira, 2000; Hestenes, 1987; Schwarz et al., 2009). From the development of atomic models to climate change simulations, models help scientists develop abstracted representations which can be used to understand and predict the structure and interactions of various phenomena. Science education reform documents support the goal of producing a scientifically literate population; one that not only understands overarching scientific concepts, but also engages in the scientific enterprise (National Research Council [NRC], 1996; NGSS Lead States, 2013). Due to the importance of modeling in scientific practice, numerous science scholars argue that science instruction should place greater focus on students working with models to understand the natural world (Campbell et al., 2012; Gilbert, 1991; Grosslight et al., 1991; Greca & Moreira, 2000; Schwarz et al., 2009; Windschitl et al., 2008). Moreover, students who participate in learning experiences focused on modeling have the potential to gain several benefits, such as deeper conceptual learning (Justi et al., 2009; Wells et al, 1995) and increased ability to engage in scientific reasoning (Malone & Schuchardt, 2023).

Teaching and learning sequences (TLSs) refer to the progression of intentional phases in formalized instruction with the purpose of engaging learners in achieving particular learning outcomes. TLSs are models to guide a teacher's instruction in a productive way. Instruction is not organized according to the whims of a teacher, but as part of a coherent framework. Within the field of science education, TLSs have been designed to help grades K-16 learners engage in scientific practices and use them to construct scientific explanations in structured lessons and units. Examples include the learning cycle approach - exploration, invention, discovery (Kaplus & Thier, 1967) - and the 5E model - engage, explore, explain, elaborate, evaluate (Bybee et al., 2006). Both of these sequences support learners with constructing science concepts while engaging in scientific practices that include asking scientific questions, data analysis, and designing scientific investigations. When teachers organize their construction according to these TLSs, there have been positive outcomes (Bybee et al., 2016). Other examples that can be applied to science education include problem-based learning (Larmer, 2015) and engineering design (Museum of Science, Boston, n.d.). In all of these TLSs, educators have given careful consideration to the nature, order and components of each phase.

Despite the advantages of and interest in TLSs, to date, the science education field lacks a review on TLSs specific to modeling. A cursory knowledge of the literature reveals that a consensus TLS for modeling does not exist. Science educators lack a comprehensive resource that brings together and makes sense of the TLSs proposed over the years. The purpose of this article is to address that gap. A review of the literature yielded 18 different TLSs focused on modeling that have been developed and articulated by science education scholars. In reviewing these TLSs, I aimed to answer the following questions:

1. What are the points of convergence and divergence across the TLSs?
2. What are considerations for science education researchers and scholars in the future based on those points of convergence and divergence?

This article is organized by four ensuring sections: (1) defining models and modeling, (2) articulating the methodology (3) presenting the findings, and (4) discussing final conclusions. These sections are addressed below.

Defining Models and Modeling

In the context of science education, models are "specialized representations that embody aspects of mechanism, causality, or function to illustrate, explain, and predict phenomena" (Schwarz et al., 2009, p. 634). Models can incorporate representations of objects (cell, airplane), concepts (force, energy), systems (digestive system, ecosystem trophic levels), events (projected object), or processes (natural selection, photosynthesis) (Gilbert et al., 2000). Their foci may vary, from representing a narrow set of relationships (an object's speed is determined by examining the relationship between distance and time) to conceptualizing complex systems and processes (graphic organizer connecting multiple sources and components associated with the greenhouse effect). They can connect concepts of different physical scales together (drawing boiling water at the macro- and molecular level) and become generalized tools to help an individual understand a wide range of phenomena (using free-body diagrams to understand motion in two dimensions).

We rely on modeling to make sense of our experiences, constantly simulating everyday situations in our minds as we interpret events and carry out tasks (Chart, 2000). If these mental models are given attention and opportunities for formal examinations, they can be transformed into conceptual models that have predictive and interpretative power (Garnham, 1997; Ormrod, 2008). Once an individual communicates their mental model, it is said to be an *expressed model* (Boulter & Buckley, 2000). Through teaching interventions and learning opportunities, learners may be exposed to or begin constructing models that are more abstract and provide conceptual insights into phenomena and their interactions. I refer to such models as *conceptual models*. The learner's initially *expressed model* may have some conceptual components, but often contain similar depictions of the event or object under study (Grosslight et al., 1991). Through participation in specially designed learning experiences, their models have the potential to become more abstract and conceptual over time.

Gilbert (1991) argued that scientific practice is essentially "a process of constructing predictive conceptual models" (p. 73). The practice of developing models is referred to as *modeling*. It can be a means to help learners refine their mental models into conceptual models, to test explanations against evidence (Windschitl et al., 2008) and eventually encompass some compatibility with current scientific knowledge (Greca and Moreira, 2000).

Methodology

Below, I provide details of the identification criteria, selection process, and analysis procedure that guided this review.

Identification Criteria

The goal of my review was to find peer-reviewed articles or book chapters that propose a TLS for the scientific practice of modeling within the last 40 years (1985-2025). The following boundaries were placed at the outset:

1. **Teaching and learning boundary**: The purpose of the TLS needed to emphasize its potential use in grades K-16 learning contexts, rather than models or frameworks that only elucidate the nature of modeling. It is important to distinguish TLSs from learning progressions. A learning progression designates different levels of performance, and how educators might help learners advance to higher or more sophisticated levels (Schwarz et al., 2009). A learning progression is not a TLS because it does not communicate information about how learning experiences should be organized within a lesson or unit. Therefore, learning progressions on modeling were not included in this review.
2. **Modeling focus boundary**: The TLSs for this review needed to articulate at least two phases dedicated to some aspect of modeling, rather than just one phase for modeling within a broader framework. The purpose of this review is to understand TLSs for which modeling was a central feature.
3. **Clear description and rationale boundary**: This boundary required that articles or book chapters referencing a TLS not just share a table or figure of a TLS, but also dedicated space for explaining the rationale of the TLS and/or a clear articulation of each phase of the TLS.

Screening & Inclusion

I conducted a search across peer-reviewed books and journal articles in science education. The search proved to be challenging, however, because of the following reasons:

1. There is a vast amount of literature related to modeling and science education. An initial search in the ERIC database combing the words, *modeling*, *science*, and *education,* yielded a list of 13,303 hits.
2. There are not agreed-upon terms. People use words like *framework*, *method*, *sequence*, and *cycle* to represent a TLS, and the TLSs they propose are sometimes embedded within an empirical study (which means the titles and abstracts might be related to the findings of the study more so than the TLS).

Decisions had to be made to narrow the search for the purpose of practicality. I conducted the search for peer-reviewed products by searching for key words in titles and abstracts, with the justification that key words would likely be in those places if the authors dedicated space to the discussion of a TLS. In the ERIC and Academic Search Complete databases, as well as an R1 university search engine, the key words of *modeling* and *model-based* were consistently used in conjunction with words likely to be used when describing a TLS (i.e. sequence, instruction, inquiry, theory, cycle, phase, construct) in a range of permutations. The greater specificity of these searches narrowed each list of hits to approximately 50-300 articles to review at a time. I scanned each title in these lists, and reviewed abstracts that had the potential to align with the selection boundaries. I also used the university library search engine to probe exclusively for books using the words, *model-based*, *modeling*, *science*, and *education*. Chapters with potential to meet the boundaries listed above were selected for further review.

41 articles and book chapters selected from the initial searches were thoroughly reviewed. Of those, 11 fully met the boundary criteria. However, with the focus of their writing on a TLS, those authors referenced other TLSs. I subsequently combed through each reference list of the original 11 and identified 7 more peer-reviewed articles or book chapters that described a TLS. A final count of 18 TLSs clearly met the boundaries, spanning the years 1987 to 2025. A full list of those TLSs can be found in the appendix. Each TLS had a unique set of phases with respect to total number, order, and description, with one slight exception. Two authors referred to the same TLS but provided some key differences in their descriptions (both Clement and Steinberg (2002) and Khan (2007) discuss a generate-evaluate-modify cycle). Therefore, both versions of the TLS were included in the review.

It is important to note that TLSs may have been missed in the process, due to great amount of scholarship related to modeling in science education (generally speaking) and the challenges of diverse phrasing mentioned above. However, every attempt was made to be thorough during the screening process. The final set of 18 TLSs reveals patterns, tensions, and insights that can inform future work in science education.

Analysis

To document information for each TLS, I read each article/chapter and took detailed notes. Using the strategy of constructing a descriptive framework (Yin, 1994), these notes were placed into two digital spreadsheets.

To gain a foundation of clarity about the TLSs and how they were structured, my first action was to determine the major components and goals of TLS phases. In the first spreadsheet, each TLS encompassed three columns. One column included a summary of each phase of the TLS, a second column noted learner actions, and a third column noted teacher actions. Three rounds of coding ensued. In the first round of coding, I aimed to stay close to the authors' descriptions, documenting the major actions that learners and teachers were expected to take. These actions were later called 'components.' Following recommendations from Saldaña (2009), in the second round I honed the preliminary component codes into final component codes, clarifying and adjusting the meaning of each code. In the third round, I collapsed component codes into three overarching categories (Saldaña, 2009), later termed 'goals.' Figure 1 highlights an example of coding for one TLS. I display the TLS phases in order from left to right. The component codes are placed underneath the phases in the 2nd row, and then the corresponding, more abstracted goal codes are in the third row. Figure 2 provides a broad snapshot of 17 TLSs, coded at the level of the three overarching goals. This figure helps the reader see the total number of phases for each TLS, and how the three goals progress through the sequence. One TLS was not included in Figure 2 because it is completely non-linear in nature (Gilbert & Justi, 2016). This TLS is discussed in the *points of divergence* section of the article.

In the second spreadsheet, I began documenting commonalities and differences across TLSs. These notes were updated based on each successive article and continual references back to the first spreadsheet. It was necessary to continually revisit the 18 TLSs directly as the analysis ensued to update the descriptive framework with additions and clarifications. The descriptive framework served as the basis for identifying the points of convergence and divergence shared in the next sections.

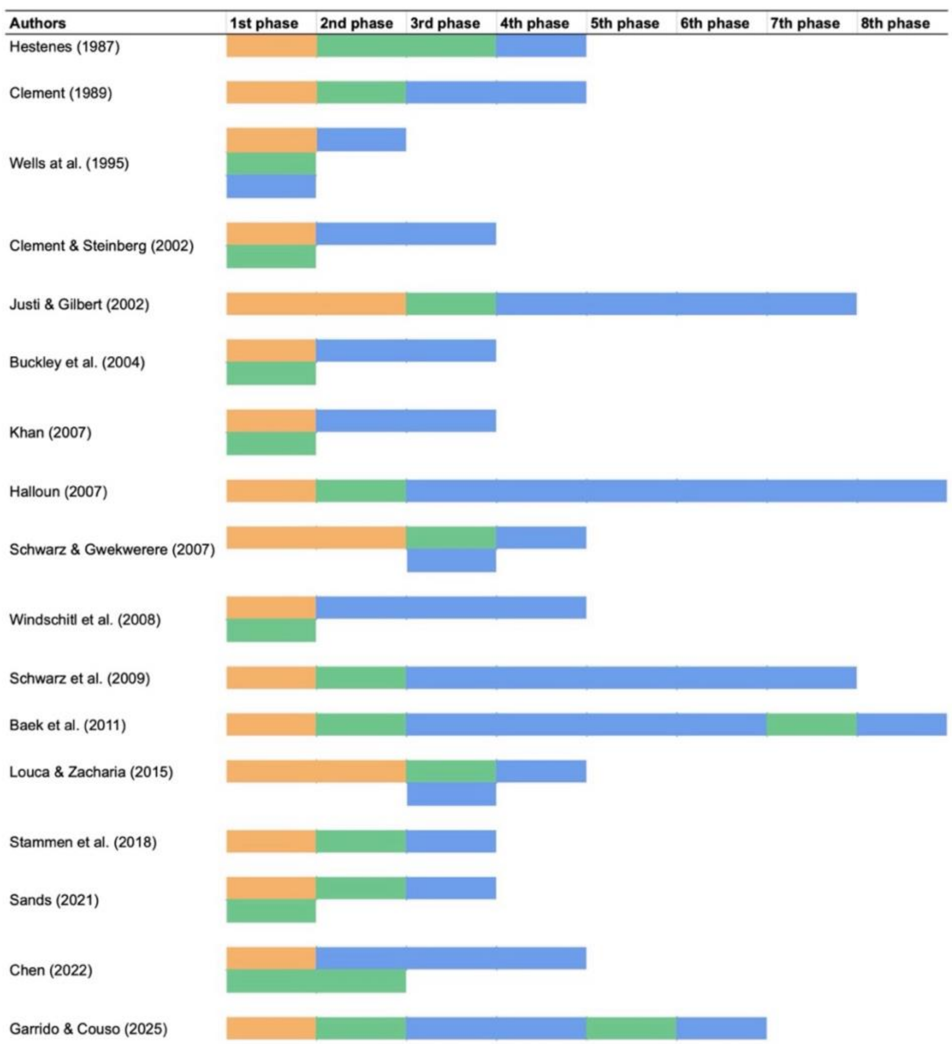
Figure 1.

Coded Components and Goals for each Phase of the TLS Developed by Garrido and Couso (2025)

IMP Cycle Phases	1. Recognize the need of a model	2. Use and express initial model	3. Evaluate model	4. Revise model	5. Express consensus model	6. Use consensus model
Coded goal component based on authors' description	• Engage with a catalyst	• Consider connections among ideas and phenomena • Express ideas through representations	• Use models to interpret and predict phenomena • Compare and evaluate models	• Revise models in light of evidence or theoretical ideas	• Consider connections among ideas and phenomena • Express ideas through representations	• Use models to interpret and predict phenomena
Coded goals	**Prepare**	**Construct**	**Use**	**Use**	**Construct**	**Use**

Figure 2.

Coded Goals for each Phase of 17 TLSs with Phases that can Progress in a Linear Sequence.



Note: Orange = Prepare, Green = Construct, and Blue = Use. Eight of the TLSs were described as non-linear, but also had a reference to a general order of events, either by numbering the phases or following arrows on a flowchart. For the purpose of Figure 2, I used the general order but note that non-linear paths are possible.

Findings

The findings are organized in two sections: (1) points of convergence, and (2) points of divergence across the TLSs.

Points of Convergence

I found that all TLSs encompassed three overarching goals for learners, with common patterns of sequencing of those goals. These two points of convergence are detailed in turn, followed by future considerations for science education researchers and scholars.

Point of Convergence #1: Common Goals

The three common goals were: (1) prepare for modeling, (2) construct models, and (3) use models. Each goal comprises at least two possible components, and every TLS utilized at least one component from each goal. While every component was not a part of every TLS, below I describe all components to better articulate the nature of the overarching goal.

Prepare for modeling*.* All of the TLSs include a component in which learners have the opportunity to prepare for the modeling process, with two options, as explained in turn.

Engage with a Catalyst. For this component, learners engage with an initial question, scenario, piece of information, or phenomenon that can serve as the catalyst for future modeling activity. This component is typically open-ended in nature (Garrido & Couso, 2025) and might include the teacher presenting a physics word problem (Sands, 2021), engaging students in generating a hypothesis after examining a data set (Khan, 2007), or asking students to consider an everyday, relatable phenomenon (Baek et al., 2011). During this component, learners may begin to engage in analogous thinking (Clement, 1989).

Engage in Pre-modeling Empirical Investigations. Learners may prepare for modeling by recording observations (Louca & Zacharia, 2015) or completing laboratory activities (Wells et al., 1995; Windschitl et al., 2008). This component privileges systematic data collection.

Construct models*.* Across all TLSs, learners are constructing models. To accomplish this goal, they may be prompted to consider connections among ideas and phenomena, consider causal relationships between variables, and/or be explicitly asked to express ideas through particular representations.

Consider Connections Among Ideas and Phenomena. TLSs describe this component as explicitly thinking about and comparing ideas with a question, scenario, prior piece of information, or investigation. This typically leads to an elicitation of their initial ideas to explain a phenomenon. As Garrido and Couso (2025) articulate it – "an explicit reference to the objects and relationships, principles, and so forth behind the students' predictions, hypothesis or initial explanations" (p. 404).

Consider causal relationships. When generating explanations of phenomena, one often needs to consider causal relationships, or how one variable under study directly influences another. Wells et al (1995) showcased students explicitly being asked to construct a mathematical relationship, Force = mass * acceleration, which could explain a modified Atwood machine. In doing so, students begin considering the relationships among variables; given the same mass, if force is increased, acceleration is increased.

Express Ideas through Representations. Learners may be explicitly encouraged to express their models through different types of representations, for example diagrams, concept maps, and flow charts (Windschitl et al., 2008). Representations are not limited to visual aids, however, as this component can also include verbal presentations (Wells et al., 1995) and role plays (Chen, 2022). As learners express their ideas, they may also be asked to consider the nature and purpose of models to support their thinking (Schwarz et al., 2009).

Use models*.* The TLSs placed great emphasis on students using their models. Students may be asked to use models to interpret and predict phenomena, compare and evaluate models, and/or revise models in light of evidence or theoretical ideas.

Use Models to Interpret and Predict Phenomena. Conceptual models can help learners explain what happens in the physical world. The interviews with scientists from Clement's (1989) study demonstrated that they developed their models of physical phenomena with the intention to help predict what might happen in a given scenario. Schwarz et al (2009) provide an example of an elementary student using their model of water movement and phase changes to interpret what happens inside a solar still. The student represented the evaporation of water at the molecular level and demonstrated condensation along the solar rim. In this way, the student is using their model to both interpret and predict what is happening in a real-world phenomenon. Students might begin explicitly mapping parts of their model to the phenomenon (Louca & Zacharia, 2015).

Compare and Evaluate Models. In addition to explaining phenomena, learners will be able to strengthen their models if they compare and subsequently evaluate their models against one another. Chen's (2022) study pointed to the value of group presentations of 5th grade students' models of a human diaphragm. With the opportunity to compare and evaluate, learners are internalizing meaning and figuring out how different representations and designs might supplement or modify their developing knowledge. As learners evaluate their models, they may be asked to consider the criteria for revision (Baek et al., 2011), or how data helps them think about the theoretical parts of the model (Windschitl et al., 2008).

Revise Models in Light of Evidence or Theoretical Ideas. When students use their models to understand phenomena, they may find inconsistencies between what their models' explanatory or predictive value and what they observed or logical arguments posed to them. This may lead to a consideration of changing and/or revising the model. As an example, Khan (2007) describes a teaching episode within a generate-evaluate-modify sequence, during which students constructed models supporting the notion that high molecular mass of a substance results in higher boiling points. When they tested this model against teacher-provided data, they found that hydrogen bonding was a better determinant for boiling point, and thus revised their model to reflect this relationship. In an example of Stammen et al.'s (2018) TLS, high school students often revise their models of DNA replication based on an analysis of provided data.

Point of Convergence #2: Common Patterns of Sequence

In addition to sharing three overarching goals, there were common trends in the sequencing of these goals across all TLSs. Figure 2 highlights diversity in the number of phases. However, it highlights important commonalities in the sequencing of the goals:

- All 17 TLSs that includes a potential linear sequence of phases begin with the goal of preparing for modeling

- The goal of constructing models always follows initial preparation, whether it occurs within the same phase as preparation or has its own dedicated phase
- The goal of using models always follows the goal of constructing models, whether those two goals are in the same phase, or when the goal of using models occurs in a subsequent phase
- The final phase of all 17 TLSs includes the goal of using models

This common sequence – preparing before constructing and constructing before using – helps us see a strong point of convergence in how different science education scholars are conceptualizing modeling in grades K-16 learning contexts.

Future Considerations

Researchers and scholars engaging with TLSs for modeling are encouraged to do the following:

- Relying on the strong foundation of the commonalities mentioned above, consider reviewing TLSs being used in work with teachers to see if gaps exist with certain components or goals and how they can be strengthened or become more explicit.
- When developing new TLSs that include other components, goals, or goal sequences, consider using the commonalities in this article as a normative reference of comparison. New variations can now be better understood and unpacked when compared to shared understandings of the past.

Points of Divergence

While there is commonality in the sequence of overarching goals, there are also several key differences that emerged from my examination. Each of the five points of divergence are explained below with illustrative examples across the TLSs. In this section, I provide future considerations for each point of divergence.

Point of Divergence #1: Model Evolution or Scientific Inquiry as the Organizing Feature Illustrates Different Emphases on a Few Key Components and the Extent of Instructor Guidance

Across several of the TLSs, two different organizing features emerged. This difference can be best articulated from a comparison of Clement's work on the one hand (and those who cite him as an influence), with several other scholars on the other hand (e.g. Chen, 2022; Halloun, 2007; Schwarz et al., 2009; Windschitl et al., 2008).

The model evolution focus. Clement (1989) presented a model construction cycle in an influential chapter from the *Handbook of Creativity* (Glover et al., 1989). The cycle is based on how scientists engage in hypothesis development and gives considerable attention to the cognitive complexities involved with constructing and refining mental models. First, initial model construction, which occurs when encountering a phenomenon or scenario, influences and is influenced by observations and the activation of analogies. Drawing on the analysis of think-aloud protocols in which scientists were asked to develop explanations for vexing physics scenarios, Clement (1989) asserted that analogy (in conjunction with prior knowledge) plays a crucial role in generating hypotheses and models. As an example, one think-aloud participant developed an analogous case of pushing on a lever to explain the optimal place to push on a wheel when rolling it up the hill. A person's formation of an analogous case to the phenomenon under examination can serve as an initial model or prompt new questions or observations to consider. Additionally, the eventual explanatory model has analogous features that relate to the target phenomenon.

Clement's (1989) cycle allows for a model testing phase that must include the possibility of continual modification through "a series of successive refinements" (p. 347); hence the phrase, model evolution. Based on Clement's cycle (1989), the *model of modelling framework* was developed and discussed in two publications (Gilbert & Justi, 2016; Justi & Gilbert, 2002). Again, the critical role of model revision was highlighted in this framework, suggesting that learners need to be able to engage in significant revision processes after an initial construction phase.

Examples of modeling in action are detailed in the exploration of a high school student learning about energy transformation and electricity through tutoring (Clement & Steinberg, 2002) and in the description of a protocol for modeling in a life science class (Clement, 2008). In these examples, the focus is on model evolution, or scaffolded refinements in the initially expressed model. In the electricity example, there is a back and forth between demonstrations and trying out ideas with a circuit kit and probing questions from the tutor. Through the use of "small analogies" and "small discrepant events" (Clement & Steinberg, 2002, p. 440), the goal of the tutor is to challenge the student's erroneous ideas in the support of a revised and more accurate model. In one specific discussion, when the student asks, "Do all wires have a tendency to want to...[have equal inflows and outflows]?", the tutor replies, "No. Now, knowing that that doesn't have to be true, think about this again" [continues to ask a probing question about the concept of pressure in a circuit] (p. 411). The same continuous cycle of generating, evaluating, and modifying iterations of a model is described in the life science class as well. Clement (2008) presented an example of an eighth-grade class engaging in continual changes of their jointly constructed model of human lungs. These changes were made after discrepant questions from the teacher, e.g. "Does your model show air going out the bottom of the lung into the body?" and "Are there operations where they remove one lung" (p. 13)? These examples clearly allow for a significant amount of teacher planning, guidance, and discursive intervention. While constantly engaged in questioning and eliciting students' ideas, Clement's (2008) sequence is "teacher directed about 85% of the time" (p. 15). This degree of teacher guidance is supported by Khan's (2007) study, in which an undergraduate chemistry instructor engaged in many directive actions, e.g. demonstrating how to read data sets, selecting variables for students to test, and selecting extreme cases to push students' thinking.

In addition to analogies and revision, Justi and Gilbert's (2002) flow chart brought a new delineation to modeling as a sequence - separate steps for (1) producing a mental model and then (2) expressing that model in various modes of representation, which refer to media through which models are developed and communicated (Boulter & Buckley, 2000). These modes include concrete (3D material constructions), verbal (description, explanation, narrative), visual (diagram, simulation, animation), mathematical (formulae, equations), gestural (body movements), and any mixtures of the five (e.g., verbal and visual).

The scientific inquiry focus. Windschtil's et al.'s (2008) articulation of a TLS is rooted in an argument for authentic scientific inquiry. They provide a historical backdrop of *the scientific method*, a common sequence that developed largely from the work of John Dewey (1910) as a heuristic for science learning, which proliferated through science education curricula throughout the 20th century. They argued its linearity, assumption of 'one' method, and lack of focus on epistemic activity all make it an unsuitable organizer of instruction. As a replacement, they developed and proposed "model-based inquiry." They developed this approach based on the epistemic practices of scientists: "we must first identify core knowledge producing activities that scientists engage in, then consider current classroom practice in light of these" (Windschitl et al., 2008, p. 943). The four phases are rooted in five features of scientific knowledge – namely, that it is testable, revisable, explanatory, conjectural, and generative. The proposed outcome is not only a model, per se, but the use of a model to construct a defensible, evidence-based explanation. The four phases are conversations that engage learners in (1) Organizing what we know and want to know; (2) Generating testable hypotheses; (3) Seeking evidence; and (4) Constructing an argument.

For those authors whose conceptual anchor is modeling as a scientific practice, more priority seems to be given to students engaging in an empirical investigation within the TLS. Windschitl et al. (2008) note that empirical investigations are not an absolute requirement in conversation #3, but many of their example prompts point to that aim (p. 958):

- "How can we operationalize our variables in ways that will allow us to record unambiguous measurements?"
- "What will it mean to collect data "systematically""?
- "To test our hypothesis, should we observe the phenomenon as it is or actively manipulate some variables while controlling others?"

Other scholars whose approach is rooted in authentic scientific practices seem to privilege students engaging in the design, data collection and analysis of empirical investigations. They have set aside specific phases for empirical investigation, either as a pre-modeling activity (Schwatz & Gwekwerere, 2007; Wells et al., 1995) or as a learning experience to take place after the initial construction of a model (e.g. Baek et al., 2011; Halloun, 2007; Louca & Zacharia, 2015; Schwarz et al., 2009). Schwarz and Gwekwerere (2007) assert that the *investigate* phase of their EIMA framework should give "high priority for data collection and analysis of those data into patterns" (p. 160). Halloun's (2007) approach includes two phases for empirical investigation. The author articulates and provides examples of how modeling is "teacher-mediated" (p. 3) but also points to times when they must step back: "all through the actual investigation process, the teacher retracts from the arbitration role to supervise the process from a distance as a moderator" (p. 26). Wells et al. (1995) noted the importance of allowing students the opportunity to design their own investigations: "the teams are permitted to pursue their own experimental procedures without intrusion from the instructor" (p. 616).

In addition to empirical investigation, another emerging and highlighted feature from the scientific inquiry TLSs is to engage learners in metamodeling prompts as they construct and use models. The goal, here, is for students to reflect on the norms of modeling as they engage in the practice itself (Schwarz et al., 2009). For example, in association with the component of *expressing ideas through representations* (constructing models), Schwarz et al.'s (2009) TLS asks learners to consider the nature and purpose of models as part of that component. The scholars who are explicit about engaging students in discussion about the qualities for evaluation and revision of models (Baek et al., 2011; Chen, 2022; Windschtil et al., 2008) tend to nest themselves in the science inquiry foundation. Students are prompted to consider questions like "How can I negotiate my model?" (Chen, 2022, p. 392) and "How do the data help us infer about theoretical (unobservable) events in our model?" (Windschitl et al., 2008, p. 959), thereby adding an extra dynamic to the goal of using models.

Comparison of foci. The model evolution approach from Clement and Steinberg (2002), and those who cite Clement's model construction cycle (1989) as major influences (e.g. Gilbert & Justi, 2016; Justi & Gilbert, 2002; Khan, 2007) tend to focus on mental modeling. This focus originates in the cognitive sciences. Clement (1989) references the constructs of conceptual change and mental processing, and both Justi and Gilbert (2002) and Khan (2007) reference cognitive psychologists, such as Johnson-Laird (1983). In turn, their focus on mental processing seems to have given rise to the inclusion of analogical thinking and the different media by which we *express* representations (e.g.

referring to *modes of representation* more so than representations as final products). Rather than emphasizing these types of references when building the justification for a TLS, scholars focused on the scientific inquiry perspective are more likely to cite literature that highlights the authentic practice of modeling within disciplines of science (Windschitl et al., 2008) and calls for reform in science education to reflect that authenticity (Louca & Zacharia, 2015; Schwarz et al., 2009). This focus is more likely to be accompanied with phases that privilege empirical investigations and opportunities to engage in metamodeling discussions about modeling as they construct and use models. The delineation is by no means perfect, as one can find references across the TLS articles that mention mental modeling and scientific practices or inquiry. However, the differing emphases across these two camps brings about helpful considerations for those will engage learners in modeling TLSs in the future.

Each of the four actions in this comparison has value. From the model evolution perspective, both analogical thinking and modes of representation are important. Regarding analogical thinking, learners consider their prior knowledge and seek associations between the phenomenon under study and prior knowledge as well as previous phenomena they have encountered (Clement, 1989). In some cases, these analogies can end up being unhelpful due to erroneous connections (Dolphin and Benoit, 2016), and so placing emphasis on analogical actions while constructing and using models can be helpful. Regarding modes of representation, the emphasis on the medium of representation instead of representations as products can be powerful. Many of the representations listed in TLSs are visual products, like diagrams (Windschitl et al., 2008) and dioramas (Garrido & Couso, 2025). Bending toward the perspective of representational *modes* opens up many options for learners to consider. The students in Chen's (2022) study relied on gestures through role play as they enacted a model of the human diaphragm. Using chairs as diaphragms and students playing the role of air molecules, they were able to represent the relationship between space and pressure through movement. Fackler and Ruth (2024) found that elementary pre-service teachers simultaneously "used their gestures, drawings, and verbal expressions as a central component of their thinking about molecules getting, having, and releasing energy" (p. 11). Their study supports the argument that the deployment of multiple modes of representation can contribute to meaningful learning when students engage in modeling.

From the scientific inquiry perspective, engaging learners in empirical investigations and metamodeling discussions are also worthwhile endeavors. Designing and conducting investigations has a long tradition in science education reforms (NRC, 1996; NGSS Lead States, 2013), to engage students in a considerable facet of scientific work. Students have the opportunity to participate and understand the important role of empiricism in generating scientific knowledge, which supports their developing understanding of what science entails (i.e., their science literacy). Indeed, understanding the role of inquiry in science is thought to be a central aim in producing a scientifically literate population (Lederman, 2007). The integration of metamodeling discussion into the goals of constructing and using models parallels previous calls for understanding scientific inquiry. These metamodeling discussions will help them understand the nature of the scientific practice.

Future Considerations. Researchers and scholars engaging with TLSs for modeling are encouraged to do the following:

- Consider both foci (model evolution and scientific inquiry) when developing or deploying the TLS with teachers and students.
- For TLSs that may be rooted in one focus over another, consider updates to the TLS that more explicitly integrate the other focus. An example of this integration is provided in Table 1 by comparing Clement and Steinberg's (2002) model evolution focus with Windschitl et al.'s (2008) scientific inquiry focus. The point of Table 1 is not to criticize the two TLSs but to illustrate what these considerations might look like in practice.

Table 1.
Example of Including the Model Evolution Focus and Scientific Inquiry Focus into TLSs

TLS Focus	TLS phases	Possible actions to include from the other perspective	Components aligned to actions from the other perspective
Model evolution (Clement & Steinberg, 2002)	Generate Model 1		
	Evaluate Model 1 • Learners experience observation discrepancies and consider analogous case • Learners modify model to…	Engage learners in an empirical investigation	Empirical investigation
	Modify Model 1 into Model 2	Engage learners in metamodeling questions: • How does the model help me connect two ideas? • What parts of my model are not helping me explain the phenomenon?	Metamodeling about constructing and using models
Scientific Inquiry (Windschtil et al., 2008)	*Conversation 1 – Organizing what we know and what we want to know.*	Engage learners to consider which modes of representation (visual, verbal, mathematical, gestural, and concrete) will be most useful.	Modes of representation
		Consider potential analogies to help learners make the initial leap from phenomenon to the initial model.	Analogies
	Conversation 2 – Generating testable hypotheses.		
	Conversation 3 – Seeking evidence.		
	Conversation 4 – Constructing an argument.	Support learners in the use of analogies to help explain the phenomenon	Analogies

Point of Divergence #2: The TLSs Differ with Respect to Being Linear or Non-linear

The second issue of divergence is linear vs. non-linear TLSs (see the appendix for the designation of each one).

Description. Of the 18 TLSs, ten are presented as linear, with one phase proceeding to the next in one direction. This could occur as a vertical list of phases, such as the case of Sands (2021) or Baek et al. (2011). Or, this could be described as a cycle yet with no indication of moving in any direction but forward, such as the case of the GEM cycle described by Khan (2007).

Eight of the TLSs are non-linear or have non-linear options. Seven have an overarching linear path one can follow, but the representations of the TLS and/or authors denote that one can move back and forth across the phases or there are points of divergence with options to move toward one phase or another. For example, Chen (2022) lists four phases vertically, but with one double arrow running across all phases, noting:

> It is important to understand that this framework does not reflect a linear process, even if represented in a linear manner. The process of modeling is a dynamic, iterative, and cumulative practice in which teachers often move back and forth between different phases depending on how the various epistemic uncertainties occur and are managed across phases. (p. 388).

Such declarations are common among the non-linear TLSs. Windschitl et al. (2008) share it is "rarely the case" (p. 960) that their overarching sequence would proceed exactly in the order of their four conversations, referring to how scientists' work would unfold: "scientists often learn things that put them back into conversations about the models and assumptions they are working from" (p. 960). Both Buckley et al. (2004) and Justi and Gilbert (2002) present their TLSs in the form of a flow chart, following the actions of a modeler. For Buckley et al. (2004), once a learner forms a mental model and interacts with phenomena or other models in the curriculum, they might go in one direction and begin evaluating the model or go in the other direction and revisit or add new information to their existing model. Garrido and Couso (2015) built in a mini-cycle of learners expressing, using, and revising models, before moving on to the next phase of building a consensus model.

One of the non-linear TLSs is unique from the other seven. Gilbert and Justi's (2016) version 2 of their *model of modelling framework* is represented as a tetrahedron with four vertices that are all equidistant from each other (each vertex represents a phase). Modelers in this TLS will engage in creating, expressing, testing and evaluating models in any particular order or sequence, with no preference for the entry point: "the use of this geometric shape emphasises three essential characteristics of the process: to be cyclic, non-linear, and not predetermined" (p. 36). In a departure from their first *model of modelling framework* (presented in Justi & Gilbert (2002) and Gilbert & Justi (2016)), version 2 "was produced by having in mind that modelling is a scientific epistemic practice" (p. 36), a nod to similar arguments from Windschitl et al. (2008).

An underlying reason for the two different approaches is not explicitly clear. As mentioned above, it would make sense for those scholars rooted in the scientific inquiry perspective to privilege non-linear TLSs, but this is not always the case. The inquiry perspective has led to linear sequences (e.g. Louca & Zacharia, 2015), and Buckley et al. (2004)'s approach cites previous mental modeling research and presents a non-linear path. The one intriguing trend is this: of the five TLSs that provide an example of modeling in elementary contexts (Baek et al., 2011; Chen, 2022; Louca & Zacharia, 2015; Schwarz & Gwekwerere, 2007; Schwarz et al., 2009), four present linear sequences and one (Chen, 2022) was presented in a mostly linear way.

It is possible that those science education researchers working in elementary contexts are inherently thinking about the clear articulations and scaffolding needed to support early learners. A linear sequence has the potential to reduce the cognitive load for both learners and teachers. Baek et al. (2011)'s TLS included eight phases, with actions broken up into clearly articulated actions. There is a clear phase for constructing the initial model, then engaging in an empirical investigation, then engaging in scientific ideas and computer simulations, and so on. When comparing the flow charts of Buckley et al. (2004) and Justi and Gilbert (2002) with the TLS of Baek et al. (2011), it becomes evident that the former TLSs give insight into the thinking processes a modeler undertakes, while the latter TLS provides more cues for a teacher about how the time will be organized. For example, Baek et al.'s (2011) phase dedicated to peer evaluation seems to point to how the students should interact in a typical classroom setting. This may explain why several of the TLSs applied to elementary contexts include a greater number of phases, each with a specific set of actions and at a fairly small grain size (e.g. Baek et al., 2011; Garrido & Couso, 2025; Schwarz et al., 2009).

The partnership between elementary contexts and linear TLSs raises the broader question of whether non-linear TLSs influence teachers' planning. Cases of significant flexibility and non-linearity are difficult to find. For example, an examination of learning activities in Buckley et al's (2004) study resembles a typical curriculum in which one activity proceeds to the next without a clear mapping back to their non-linear TLS. There are a few cases of a teacher combining two phases, but still in a mostly linear sequence. The description of learning experiences in Chen's (2022) study suggests the teacher completed phase 1 entirely before moving on (problematizing a phenomenon), then engaged in a back and forth of phase 2 and 3 (material practice and argumentative practice), then completed phase 4 (conceptualizing theory and application of final models). Mendonça and Justi's (2011) study of middle school chemistry students in Brazil tested the use of the *model of modeling framework* (Justi & Gilbert, 2002). The list of learning experiences presented in table format follows the flowchart in a mostly linear fashion, proceeding along four ordered sub-processes, but occasionally including two sub-processes together (e.g. sub-processes 1 and 2 occurring together, producing a mental model and expressing it in modes of representation). Despite these findings, one can argue that an overly linear sequence can make it difficult to maintain connections to authentic scientific practice (Windschitl et al., 2008).

Future Considerations. Researchers and scholars engaging with TLSs for modeling are encouraged to do the following:

- For those using linear TLSs, consider representing instances of moving back and forth across actions or components when they're implemented in K-16 learning contexts. Where might there be opportunities to represent that back and forth within the TLS?
- For those using non-linear TLSs, consider the extent of non-linear actions among modelers and whether those actions can be bundled together in a clear phase that guides a teacher's planning.

In Figure 3, I present an example of the difference between an idealized model and an implemented model from Chen's (2022) article. The model presented in the introduction of the article includes four separate phases, but with options to move back and forth among them. However, as mentioned above, during implementation, only phases 2 and 3 were combined. While this was only one iteration of implementation, if such a reality was observed repeatedly, it could lead to a modification of the TLS. In the bottom row of Figure 3, the TLS has three overarching phases while acknowledging an inherent back and forth between material and argumentative practice in phase 2. Perhaps that update would be misguided after more attempts at implementation, but the Figure illustrates an example of balancing the benefits of a mostly linear sequence and maintaining authenticity in scientific work.

Figure 3

Comparison of Chen's (2022) Introduced and Implemented TLS

<table>
<tr><td>Chen's (2022) TLS</td><td colspan="4">Phases progressing left to right</td></tr>
<tr><td>TLS presented in introduction</td><td>1. Problematizing a phenomenon</td><td>2. Material practice</td><td>3. Argumentative practice</td><td>4. Conceptualizing theory and application of final models</td></tr>
<tr><td>TLS based on description of unit implementation</td><td>1. Problematizing a phenomenon</td><td colspan="2">2. [Combined phases]
Material practice
(develop and explain models)
⇕
Argumentative practice
(evaluate and revise models)</td><td>3. Conceptualizing theory and application of final models</td></tr>
</table>

Point of Divergence #3: The Total Amount of Time Needed to Complete a TLS is Rarely Clear, and Differences in Duration Appear to Exist

It is the nature of TLSs to have some flexibility in implementation, particularly with regard to the total length of time it takes to implement it. Nonetheless, it is important to share the finding that a substantial range of possible timeframes appears to exist. I use the word 'appear' because there is not a common unit that authors use when providing examples of the TLSs during implementation.

Description. At one end of the continuum, Schwarz et al.'s (2009) 7-phase TLS was applied to 6-week units in 5th and 6th grade classrooms. While it is not clear how days, lessons, or hours were spent on the unit, interview references to "lesson #15" seem to imply a lengthy total duration (p. 645). At the other end of the continuum, Khan's analysis of generate-evaluate-modify cycles in an undergraduate chemistry course revealed that the instructor facilitated 52 total cycles across a semester, with an average of 2 cycles per class period. Stammen et al.'s cycle did not include a timeframe, but after reading the example of high school students developing possible models of DNA replication with pop beads and chenille stems, it seems the activity (or a modified version of it) could be completed in a class period or two since there is no need for extensive experimental design. The number of phases does not necessarily translate to the total duration, as Wells et al.'s (1995) TLS only consisted of two phases but can take 2-3 weeks to complete (there is considerable work to be done in their 'model development' phase). Some TLSs can be completed in about a week; the *model of modelling framework* (Justi & Gilbert, 2002) has been implemented during five in-class activities (Justi et al., 2009). The key issue here is that time is very important to teachers, as they consider how to parse and organize it when making decisions (Hargreaves, 1994). Yet, currently, unless the author of the TLS is working directly with the teacher, it is not clear what teachers should expect with regard to total time, relative time on each phase, and the adaptability of the TLS to be implemented in shorter or lengthier timeframes.

Future Considerations. Researchers and scholars engaging with TLSs for modeling are encouraged to do the following:

- Since references to weeks or lessons do not provide a common unit of understanding, consider reporting projected or implemented timeframes in the unit of *instructional hours*.
- Consider reporting projected or implemented timeframes for each phase in the TLS

Point of Divergence #4: The TLSs Differ with Respect to the Extent of Information Regarding Teachers' Actions, with Most TLSs Written from the Learner's Perspective

The TLSs varied in how they wrote about and described the TLS.

Description. For the majority of TLSs, the description of phases is written primarily from the learner or modeler's perspective, a concern noted by Garrido and Couso (2025) prior to developing their TLS. Most often, a description of what the learners are doing accompanies the title or summary of each phase. Examples of learner actions include considering an introductory phenomenon, exploring relationships among variables, expressing mental models, and sharing and revising those models after opportunities to test them. The role and actions of the teacher are not as clear. In 16 of the 18 articles, the teacher's actions were explicitly described for some (but not all) phases or for none of the phases. A breakdown is provided below.

- 9 TLSs include only the learners' perspective for each phase
- 7 TLSs includes the learner's perspective and partially the teacher's perspective

- 1 TLS includes only the teacher's perspective for each phase
- 1 TLS includes both the learners' and teacher's perspectives for each phase

There is value in describing both the learners' and teachers' role when communicating about science instruction, as the reader can better imagine and simulate the phase when considering both perspectives. Be it for science education researchers, curriculum developers, or science teachers, describing both learner and teacher actions helps to communicate a fuller scope of each phase.

Table 2 presents an example of comparing the described actions across two TLSs. Baek et al. (2011) describe the learners' actions for their *peer evaluation phase*, and Garrido and Couso (2025) describe both learners' and the teacher's actions in their *express consensus model* phase. These two phases are at similar places of their respective TLSs (toward the end). The purpose of making this comparison is not to criticize Baek et al.'s (2011) TLS, as they provide clear and helpful learner descriptions of each phase. In addition, there is a mention of a teacher giving a "mini-lecture" (p. 203) when describing the implementation of a particular unit, but actions like this are not articulated in the table that presents each phase. Rather than serving as a source of criticism, the comparison helps the science education community understand what can be gained from being just as descriptive about the teacher's role as we are the learners' role. At a general level, all articles acknowledged the importance in the teacher's role to bring about and support meaningful learning in the TLSs. Meaning-making in science classrooms relies on both dialogic and authoritative discourse, and the learning experiences – whether more controlled or more open-ended – are introduced and monitored by the teacher (Halloun, 2007; Mortimer & Scott, 2003; Sickel et al., 2013). In Garrido and Couso's (2025) description of the *express consensus model* phase, we learn important responsibilities of the teacher - guiding a class discussion, promoting the sharing of errors and challenging ideas, and ensuring the funneling process leads to a consensus model that is scientifically accurate.

Table 2

Learners' and Teachers' Actions for Baek et al's (2011) Peer Evaluation Phase and Garrido and Couso's (2025) Express Consensus Model Phase

Authors	Learners' actions	Teachers' actions
Baek et al., 2011, p. 201	• "each student presents his/her model and the others give their evaluative feedback on it" • [students] "discuss criteria for evaluating models"	
Garrido & Couso, 2025, p. 406	• "students' models are shared and made public among the entire group"	• Guide "a collaborative negotiation and synthesis of students' explanations into a completer and more sophisticated final consensus model" • "cultivate a positive and secure classroom environment wherein errors are embraced" • make sure the final model "is aligned, similar, and coherent to the instructional target"

Future Considerations. Researchers and scholars engaging with TLSs for modeling are encouraged to do the following:

- Consider describing the phases from the perspective of learners' actions/roles *and* the teacher's actions/roles, to communicate the nature of the phase more completely to readers.

- If educative curriculum tools accompany the TLS, consider uploading them online as supplementary items to the published article.

Point of Divergence #5: There are more Examples of the TLSs within the Physical Sciences when Compared to Life Science and Earth Science

Articles and book chapters under this review were selected if they dedicated space to proposing and describing a TLS. In 13 of the 18 articles or book chapters, the author(s) also supplied an articulated example of the TLS in action and how it might unfold in a classroom. In the following section, I discuss these examples in accordance with the science disciplines represented.

Description. The following science disciplines were represented across 13 TLSs as shown in table 3 below. Louca and Zacharia (2015) provided two examples in their article, one in physical science and one in life science (hence, the total number of examples is 14):

- 10 articles discussed physical science examples
- 3 article discussed life science examples
- 1 article discussed an Earth science example

Table 3 presents a breakdown of the example topics organized by grade band, author, and science discipline.

Table 3
Topics Addressed in Examples of TLSs

Science discipline	Author(s)	Grade Band	Topic(s)
Physical sciences	Clement (1989)	University doctoral students	Mechanics
	Hestenes (1987)	University undergraduate	Mechanics
	Wells et al. (1995)	University undergraduate and secondary	Mechanics
	Sands (2021)	University undergraduate	Mechanics
	Khan (2007)	University undergraduate	Vapor pressure and boiling point
	Clement & Steinberg (2002)	Secondary	Electric circuits
	Schwarz et al. (2009)	Middle school and elementary	Properties of matter (evaporation and condensation), and the nature of light
	Baek et al. (2011)	Elementary	Properties of matter (evaporation and condensation)
	Garrido & Couso (2025)	Elementary (participants were pre-service teachers but the topic is aligned with elementary)	Floating, buoyancy, and forces
	Louca & Zacharia (2015)	Elementary	Accelerated motion
Life science	Stammen et al. (2018)	Secondary	DNA replication
	Chen (2022)	Elementary	Human respiratory system
	Louca & Zacharia (2015)	Elementary	Plant parts and their role
Earth science	Windschitl et al. (2008)	Middle school	Motion of Earth, Moon and Sun

In the vast majority of articles, the examples that accompanied the TLSs included topics that that have a long tradition in school science; they could be investigated with common school supplies and tested in controlled settings with immediate feedback. Examples in the physical sciences include pre-service teachers using cups and water to investigate the forces involved with floating (Garrido and Couso, 2025) and a secondary student testing out ideas about the nature of electric currents using a basic circuit kit (Clement & Steinberg, 2002). For life science, elementary students used their bodies and classroom chairs to model how a lung works (Chen, 2022), and secondary students used chenille stems and beads to test out their ideas about DNA (Stammen et al., 2018).

Illustrations of the TLSs in life science and Earth science have great potential to reveal nuances that may need to be considered for those disciplines. Biology was once a discipline characterized by stores of information such as classifications of organisms and anatomical descriptions. We are now in the age of studying life at the molecular level (Flannery, 2001), which means biology relies heavily on a foundation of physical science (Fanelli & Glänzel, 2013). Due to the *physics first* movement, there are arguments for secondary students to learn physics and chemistry before they complete a biology course in 11th grade (Bybee & Gardner, 2006). Earth science is also viewed as having an overarching and integrative role in the science curriculum. OpenSciEd chose to construct their high school curriculum into the separate disciplines of biology, chemistry, and physics, but paired Earth science with each of them (Activate Learning, n.d.). Complex phenomena, such as climate change (often associated with Earth science), incorporate understandings of energy (physical science) and understandings of organic processes like photosynthesis (life science). With this perspective, conceptual models in life and Earth science have the likelihood of becoming extremely complex and abstract. Zangori et al.'s (2017) study of secondary students creating models in a unit on climate change seems to support this notion; they found that students needed to first grapple with the inner-workings of the carbon cycle before they could make meaningful connections to the more complex phenomenon of climate change.

More investigations of Earth and space science may reveal a component in constructing models that is not explicit across the 18 TLSs in this review, that of *physical scale and perspective*. As evidenced from research on levels of representation (Chandrasegaran et al., 2008) and research on students' understanding of scale (Jones & Taylor, 2009), understanding scientific concepts requires students to think about the relative scale of phenomena, from the large-scale macro world to the small-scale micro world. When constructing models, it might be helpful for learners to think about how scale of phenomena may play a role in their model. For instance, spatial reasoning and scale are both important to and can inhibit learning about Earth-Moon-Sun phenomena (Wilhelm et al., 2018). Investigations may require consideration of the sizes of the Earth, Sun, and Moon, and/or the distances between them, and how variables of magnitude can be represented within a model. Spatial orientation is particularly important when science educators rely heavily on two-dimensional models of complex phenomena. Park et al.'s (2023) investigation of 10th grade students' drawings of water and sustainability revealed that focusing on only one spatial orientation, e.g. top-down, can highlight some important components (i.e. runoff) while ignoring other ones (i.e. groundwater). Beyond an exploration of causal factors and connections among ideas and variables, *physical scale and perspective* may need more attention within the goal of constructing models.

Future Considerations. Researchers and scholars engaging with TLSs for modeling are encouraged to do the following:

- Consider including descriptive examples of the TLS within life science or Earth science learning contexts, to provide the field more examples across the disciplines and potentially uncover new factors to examine based on the nature of the discipline.

- Consider including descriptive examples of the TLS that are complex and integrative across disciplines, e.g. climate change, to understand how TLSs work with topics that cannot be investigated quickly with typical school science materials.
- Consider placing attention on the role of physical scale and perspective in modeling, and how that component may connect to an overarching modeling goal (e.g. constructing models).

Conclusion

I have reviewed the literature to understand the various ways science education researchers and scholars have developed and presented TLSs for the scientific practice of modeling. In doing so, points of convergence and divergence have been examined, and future considerations have been identified. I believe those considerations provide practical advice that can help move the field of modeling education forward in productive ways. Zooming out from those considerations, I also envision that science education researchers and scholars might consider three broad research agendas in this space – what I will call the *synthesis*, *visionary*, and *scalability* agendas. I advocate that working across these agendas will be helpful, because they will push and pull on one another as the modeling education field pursues its potential while also thinking about issues of practicality and diverse learning contexts.

The **synthesis agenda** would be concerned with developing a meta-model based on the extant literature. The meta-model might be organized by the common goals and sequencing from this review (see points of convergence above). It would inventory the range of components and goals, including those identified in future TLSs, ensuring the modeling evolution and scientific inquiry perspectives are balanced and taking stances on other key points of divergence (e.g. the issue of linearity and the need for projected timeframes). The meta-model would be developed from the argument that it is built off a foundation of over 30 years of prior TLSs, and therefore benefits from a strong foundation across multiple academic lineages.

The **visionary agenda** would be concerned with developing TLSs in alignment with particular visions. In many ways, prior TLSs have been visionary. Clement's work took a careful look at the cognitive intricacies of modeling and opened up new avenues for designing learning sequences in ways that helps learners refine their mental models. Windschitl et al's (2008) model-based inquiry proposed a very different way of thinking about scientific practice in the classroom (when compared to "the scientific method"), allowing for a learning environment characterized by active learning and epistemic agency. Researchers and scholars should continue to pursue visions that are in support of improving science education, and how TLSs for modeling can be designed to support those aims. For example, what TLSs for modeling might best support learning complex socio-scientific and interdisciplinary topics?

Finally, the **scalability agenda** would be concerned with developing and testing TLSs in the pursuit of discovering what is most scalable across a wide range of learning contexts. Currently, there is no evidence that sophisticated modeling-based teaching is occurring at a large scale. Individual research teams are trying out their TLSs with groups of teachers (e.g. Schwarz & Gwekwerere, 2007) and often find that the adoption of those TLSs is quite challenging and ambitious for them (e.g. McLaughlin & Pringle, 2011; Wells et al., 1995; Windschitl et al., 2008). The scalability agenda would need to begin with an approach that is rarely a starting point in the science education community; the premise that school is a very different place from a science laboratory and that teachers have general learning goals for their students beyond learning science (Friedrichsen & Dana, 2005). It would take an asset-based perspective, starting with the proposition that teachers have knowledge in areas that we do not sufficiently consider. Teachers have the responsibility to cultivate and manage socioemotional relationships and take into account what motivates their students to learn (Van Sickle

& Spector, 1996). They must differentiate instruction for learners with a wide range of accommodations and modifications based on individualized learning plans. Coming from this perspective, a TLS might be designed in collaboration with teachers (McLaughlin & Pringle, 2011) and build off of teachers' general pedagogical knowledge and responsibilities. The TLS might focus on a few phases with non-negotiable components of modeling practice but that include potential actions for differentiation and scaffolding. The TLS might need to be applicable to relatively short units of learning, because school curricula play a significant role in determining how much time can be dedicated to any one topic (Fitzgerald et al., 2019; Halloun, 2007). Researchers and scholars working under this agenda might begin with some of the components provided in the points of convergence section of this paper, but ultimately navigate the tension of engaging learners in meaningful modeling while also being consistently workable for teachers.

The final consideration for the field of science education relates to how we share TLSs in peer-reviewed outlets. In several cases, the articulation of modeling TLSs was a part of a typically structured empirical paper, which means the majority of the article space was dedicated to results and findings (e.g. Louca & Zacharia, 2015; Chen, 2022). This means there is limited space to fully articulate the rationale behind the development of the TLS and the practical knowledge that needs to accompany it. For those articles that utilize a greater amount of space for their rationalization along with an articulated example (e.g. Clement & Steinberg, 2002; Garrido & Couso, 2025; Wells et al., 1995; Windschitl et al., 2008), it is incredibly helpful for the field. In those instances, editors and reviewers were willing to consider a manuscript that was atypical in structure. More of these types of articles will be needed in the future. The literature on modeling TLSs has not reached consensus, and may never do so. However, there is excellent potential in pursuing the development, articulation, modification, and future testing of modeling TLSs in K-16 learning contexts to support the implementation of this important scientific practice.

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Appendix: Teaching and Learning Sequences for Modeling

The 18 TLSs are presented in chronological order by year of publication.
Note: Eight of the TLSs are described as non-linear. Seven of those non-linear TLSs have a reference to a general order of events, either by numbering the phases or following arrows on a flowchart. For the purpose of this table, I used the general order provided but point out the authors make it clear that non-linear paths are likely. Additionally, the list of learners' actions is a summary and does not fully encapsulate the phases. It is highly recommended that readers go to the source publication to fully understand the TLS.

Author, Year, and Name of Model or Sequence	Grade-level and Science Discipline	Linear or Non-Linear; Cycle or Sequence	Presumed Order of Learners' Actions Based on Authors' Representation and Discussion
Hestenes (1987) General model development	**Grade-level**: not specified, example is for university **Science discipline**: all; example is for physics	Linear Sequence	• *Description Stage* – Students describe the phenomenon and identify variables, and may construct initial conceptual models like free-body diagrams • *Formulation Stage* – Students consider how to develop a functional relationship between the variables • *Ramification Stage* – Students work out special properties and implications of the mathematical model • *Validation Stage* – Students test the model empirically

Clement (1989) Hypothesis development (model construction) cycle of conjecture, evaluation, and modification or rejection	**Grade-level**: not specified, example is university doctoral candidates and professors in technical fields **Science discipline**: all; example is for physics	Non-linear Cycle	• (A) Make Initial Observations & (B) Activate Possible Analogies and Related Model Elements
			• (C) Construct Initial Model
			• (D) Rational Evaluation
			  o (E) Reject or Modify Model
			• (F) Construct and Perform Empirical Tests
			  o (E) Reject or Modify Model

Wells et al. (1995) Modeling method	**Grade-level**: secondary (high school) and university **Science discipline**: physics	Linear Cycle	• *Model Development* – Students explore phenomena and develop a model to explain it • *Model Deployment* – Students test model against experiments or physics problems
Clement and Steinberg (2002) Role of analogies	**Grade-level**: not specified, example is for	Linear Cycle	• Generate Model 1 • Evaluate Model 1 o Learners experience observation

and observations in GEM cycle of model generation, evaluation, and modification	secondary (high school) **Science discipline**: not specified, example is for physics		discrepancies and consider analogous case ○ Learners modify model to… ● Modify Model 1 into Model 2 ● Evaluate Model 2 ○ Learners experience observation discrepancies and consider analogous case ○ Learners modify model for the next step ● Modify Model 2 into Model 3 ● Evaluate Model 3 ○ Learners experience observation discrepancies and consider analogous case ○ Learners modify model for the next step [sequence continues as needed]
Justi & Gilbert (2002) and Gilbert & Justi (2016) Model of modeling framework	**Grade-level**: not specified **Science discipline**: not specified	Non-linear Cycle	● Decide on purpose ● Select source for model and/or have experience ● Produce mental model ● Express in mode(s) of Representation ● Conduct thought experiments ○ Reject or Modify Mental Model ● Design and Perform Empirical Tests ○ Reject or Modify Mental Model ● Fulfill Purpose ● Consider Scope and Limitation of Model
Buckley et al. (2004) Model-based learning framework	**Grade-level**: not specified, example is for secondary (high school) **Science discipline**: not specified, example is for biology	Non-linear Cycle	● Model formation into learners' mental models based on prior knowledge or new information ● Model use ○ Interacting with hypermodels and phenomena ● Model evaluation ○ Model reinforcement or revision of the model, or ○ Model rejection and formation of a new model
Khan (2007) GEM cycle	**Grade-level**: university **Science discipline**: chemistry	Linear Cycle	● *Generate hypothesis* – Students consider relationships between variables to develop explanatory models of molecular structure ● *Evaluate hypothesis* – Students design new tests, compare ideas, and seek new information to evaluate mental models and consider causal factors ● *Modify mental models* – Students revise and

			enrich mental models to have predictive value [cycles of GEM contribute to refinement of learners' mental models]

Halloun (2007) Modeling learning cycle (MLC)	**Grade-level**: secondary and university
	Science discipline: examples are for physics
		Non-linear Cycle	• Exploration
			  ○ *Monstration* – empirical situations are exposed to support cognitive disequilibrium
			  ○ *Nominal models* – construction of a subsidiary model
			• Model Adduction
			  ○ *Plausible model* – time is devoted to the proposition and comparison of plausible models
			  ○ *Investigative design* – proposes an investigation to test the model
			• Model formulation
			  ○ *Investigation and initial model formulation* – learners collaboratively conduct the investigation and refine the plausible model
			  ○ *Rational model extrapolation* – learners rationally analyze the model and may reference previous plausible models
			• Model deployment
			  ○ *Elementary deployment* – learners deploy the constructed model in parts
			  ○ *Paridigmatic deployment* – learners deploy the model with its integrity
			• *Paradigmatic synthesis* – learners determine viability of the model and either return to previous phases for revision or begin a new cycle

Schwarz & Gwekwerere (2007) EIMA instructional framework	**Grade-level**: Elementary (used by elementary pre-service teachers) **Science discipline**: all	Linear Sequence	• *Engage* – students engage in the topic and draw on prior knowledge • *Investigate* – students investigate the topic or phenomenon through data collection and analysis • *Model* – students create models (focusing on causal aspects of patterns in phenomena) or explanations • *Apply* – students apply models/explanations to different situations
Windschitl et al. (2008) Model-based inquiry	**Grade-level**: secondary (middle and high school) **Science discipline**: all	Non-linear Cycle	• *Conversation 1 – Organizing what we know and what we want to know*. Students consider topic under study and think of ways to represent current understandings • *Conversation 2 – Generating testable hypotheses*. Students use model to articulate sets of

			relationships or events to test the model ● *Conversation 3 – Seeking evidence*. Students consider what data would help test their models ● *Conversation 4 – Constructing an argument*. Students consider whether original model is consistent with the data, how the data helps them make theoretical inferences, what the model does not predict, whether the model should change, and how to apply their models to new phenomena
Schwarz et al (2009) Instructional modeling sequence for elementary curriculum materials	**Grade-level**: elementary and middle school **Science discipline**: not specified, examples are for physics and chemistry	Linear Sequence	● *Anchoring phenomena* – consider driving questions and phenomena for a concept. ● Construct a model ● Empirically test the model ● Evaluate the model ● Test the model against other ideas ● Revise the model ● Use the model to predict and explain
Baek et al. (2011) Model-centered instructional sequence	**Grade-level**: elementary **Science discipline**: all, example is for physical science	Linear Sequence	● *Anchoring phenomena and central questions* – phenomena from everyday life are introduced ● Constructing an initial model ● *Empirical investigations* – work in groups to complete a set of investigations. Learners make and share predictions and revise models based on evidence. ● *Scientific ideas and computer simulations* – scientific ideas and theories are introduced via texts, the teacher, and simulations. ● Evaluating and revising the model ● *Peer evaluation* – present models in small groups, give and receive feedback, and discuss criteria for evaluation ● Constructing a consensus model ● Using the model to predict or explain related phenomena
Louca & Zacharia (2015) Paraphrased title: Four discrete phases of modeling-based learning	**Grade-level**: not specified, example is for elementary **Science discipline**: not specified, example is for physical science and life science	Linear Sequence	● *Collection of observations and experiences phase* – learners examine a natural world phenomenon, to identify its parts or predict/explain its behavior ● *Construction of the model phase* – learners construct an initial model. They consider how to represent concepts symbolically and how well they represent the components or features. The model is modified and enhanced.

			● *Evaluation of the model phase* – learners apply their models to new contexts, testing one component at a time, and receiving feedback. ● *Revision of the model phase* – learners may reject the model and start over, or may revise or elaborate the model.
Gilbert & Justi (2016) The Model of Modelling v2	**Grade-level**: not specified **Science discipline**: not specified	Non-linear Cycle	Four equidistant stages, with no one entry point or sequence from any one stage to another ● Expression with sub-processes (e.g. select modes of representation) ● Creation with sub-processes (e.g. make analogy, get new empirical data) ● Test with sub-processes (e.g. design test, interpret data, generate explanation) ● Evaluation with sub-processes (e.g. define scope of model)

Stammen et al. (2019)
Modeling cycle
Note: this model is cross-referenced to Malone et al. (2019), but it is explained in Stammen et al. 2019). Malone is an author of both publications.
	Grade-level: not specified, example is for secondary
	Science discipline: not specified, example is for biology
		Linear Cycle	● *Phenomena* – learners encounter phenomena
			● *Model with Representations* – learners develop a model
			  ○ Develop model based on data
			  ○ Representations may be algebraic, verbal, diagrammatic, verbal, graphical, or any combination of the four
			● *Correspondence with Phenomena* – learners use model to make predictions based on correspondence with phenomena, and continues the cycle by making revisions as necessary

Sands (2021) ACME Protocol	**Grade-level**: university **Science discipline**: physics	Linear Sequence	● *Assess the problem* – develop a mental model by identifying properties of objects ● *Construct the model* – translate mental model into a mathematical structure ● *Evaluate the model* – run the model, produce an output, and compare to known data if possible
Chen (2022) Variations of epistemic uncertainty in the four phases of modeling	**Grade-level**: not specified, example is for elementary **Science discipline**: not specified, example is for life science	Non-linear Sequence	● *Phase 1, Problematizing a phenomenon* – learners work to make sense of a phenomenon ● *Phase 2, Material practice* – learners develop mental and physical models to explain a phenomenon ● *Phase 3, Argumentative practice* – learners debate and evaluate their models based on evidence ● *Phase 4, Conceptualizing theory and application of final models* – learners conceptualize a final

			model and connect it to scientific theory
Garrido & Couso (2025) Instruction Performance Modeling (IMP) Cycle	**Grade-level**: primary and secondary, example is with preservice teachers **Science discipline**: not specified, example is for physical science	Non-linear Cycle	• Recognize the need of a model • Use and express initial model • Evaluate model • Revise model • Express consensus model • Use consensus model