Interlocking Models in Classroom Science

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Abstract

Both professional and classroom-based scientific communities develop and test explanatory models of the natural world. For students to take up models as tools for sensemaking, practice must be agentive (where students use and revise models *for* specific purposes) and conceptually productive (where students make progress on their ideas). In this paper, we explore principles to support agentive and conceptually productive modeling. One is that models can "do work;" that is, participate in students' sensemaking by offering resources, making gaps visible, or pushing back on modelers' understandings. A second is that working across, and seeking to align, multiple models—what we explain as *interlocking* models—supports models to do work. A third is that modeling activity can support fine-grained conceptual progress. We detail how we used these ideas to guide and refine the design of a fifth-grade investigation into the conservation of matter across phase change. We identify four ways that models participated in students' sensemaking as they interlocked: by providing *contradictions*, *constraints*, *representational surplus*, and *gaps* for students to engage with. We discuss how designing for models to be co-participants in sense-making and to interlock can provide productive paths forward for curriculum designers, researchers, and teachers.

Introduction

The idea that students should develop and use scientific understandings through science and engineering practice is central to reform-based efforts in science education (NRC, 2012). Researchers and educators taking up this call have sought to instantiate science practices in classrooms in ways that are useful *for* students and *from* students' perspectives, guided by the idea that students should experience their scientific activity as meaningful and useful (Berland et al. 2016; Gilbert & Justi, 2016; Russ, 2014). For many, modeling is the central practice of the scientific enterprise (Giere, 2004; Nersessian, 2008). As such, it has been used as a structure for organizing classroom learning (Kenyon et al., 2008; Lehrer & Schauble, 2015; Louca et al., 2011; Passmore et al., 2014; Windschitl et al., 2008). For example, a unit of study might involve third-grade students developing and comparing models representing where rain goes after it reaches the ground; pursuing a set of investigations related to water's phases and interaction with earth materials; and developing a class consensus model that incorporates the results of their investigations (Vo et al., 2015).

However, researchers and educators have also experienced challenges in implementing classroom modeling, including helping students take up models as tools for sensemaking and make conceptual progress through modeling (Guy-Gaytán et al., 2019; Ke & Schwarz, 2021). This paper addresses these challenges and explores how instructional sequences in which students work with and relate multiple models can support meaningful sensemaking and conceptual progress. We first present a conceptual framework that guides our work with students; specifically on *modeling for sensemaking* and *modeling as a distributed system*. We explore how these ideas have been taken up in the current literature on classroom modeling. We then develop three guiding principles for classroom modeling activity. The first is that models can "do work," that is, act as co-participants in students' sensemaking. The second is that engaging with and seeking to relate multiple models—what we explain as interlocking models (Nersessian, 2009, 2012)—supports models to do work. The third is that modeling supports fine-grained conceptual progress. We show how these ideas guided the design of a fifth-grade investigation into the conservation of matter. We then describe over the course of their investigation, students worked with different models, interlocked models, and made conceptual progress through engaging with the contradictions, gaps, constraints, and representational surplus emerging between models.

Conceptual Framework

We conceptualize modeling as re-representing complex phenomena to develop shared understandings of how and why the world works (NRC, 2012; Schwarz et al., 2009). Like others (Gouvea & Passmore, 2017; Lehrer & Schauble, 2015), we take a *modeling for sensemaking* approach, emphasizing models as tools that people use to embody and refine ideas, rather than as representations of what is already known. Models take many forms, including equations, theories, diagrams, and simulations. Modeling can involve abstracting and simplifying phenomena to explore the explanatory power of entities and relationships. It can also involve making ideas concrete by developing experiments or instruments that re-represent phenomena at scales of time and space that allow scientists to get a handle on them (Nersessian, 2012; Rheinberger, 2015). Modeling involves cycles of revision as modelers put forward provisional ideas, represent them externally, run or test models, then evaluate and refine ideas and representations.

The work of modeling is distributed across modelers, models, and the world. As Gouvea and Passmore (2017) argue, a *modeling for* view "positions models as inextricably linked to the agents who use them and the epistemic aims of their scientific practice." Accounts of professional science describe how scientists treat non-human entities, including models, as co-participants in inquiry, attributing intentionality to tools, models, and to nature (Knorr-Cetina, 2001; Nersessian et al., 2003). Pickering (1995) describes science as a "dance of agency" in which scientists enact agency by developing an account and associated models or instruments to test their accounts; step back as nature speaks through the representational form; and revise their accounts and instruments; iterating until accounts, representations, instruments, and material responses hang together.

Further, progress in modeling rarely involves the development of a single model; instead, scientific progress relies on developing a model-system made up of models of different kinds and forms (Nersessian, 2012; Rheinberger, 2015; Rouse, 2015). For example, Nersessian detailed how a lab seeking to understand neural networks worked across, and *interlocked*, a representational systems including in vitro physical models (e.g., dish of neurons and electrodes), computational re-descriptions such as simulations of animal behavior controlled by the dish, and data representations (visualizations of neural activity).

In this paper, we take up ideas of *modeling for sensemaking, modeling as a distributed system,* and Nersessian's notion of *interlocking models* for classroom design and analysis. We consider individual classroom models (e.g., simulations, empirical apparatus, molecular models) as part of model systems. Further, we emphasize the *activity* of interlocking—that is how modelers take up and relate models. We treat relations among models as made in activity, and different across moments of problem-solving. We explore how these perspectives on modeling can support the design of learning environments and address challenges that researchers and educators have experienced in classroom modeling.

Modeling in Classroom Science

Researchers have begun to take up the *modeling for* perspective in classroom work, arguing that it better represents the work of science, provides a more expansive and equitable approach, and can support conceptual process through modeling (Schwarz et al., 2022; Gouvea & Passmore, 2017; Salgado, 2021; Suàrez, 2020). Modeling can invite students into the tentative and revisable nature of scientific work (Lehrer & Schauble, 2015; Windschitl et al, 2008), lend coherence to activity (Passmore & Svoboda, 2012), and focus attention on entities and relations that explain phenomena (Louca et al., 2011; Schwarz & White, 2005; Tobin et al., 2018). Researchers taking a *modeling for* perspective have argued that modeling is a powerful practice when students are positioned as epistemic agents and take up modeling for purposes such as explanation and prediction.

Researchers have developed descriptions of what a *modeling for* perspective might look like in classrooms; providing a set of goals for researchers and educators to work toward. In these descriptions, modeling is used in service of students' sensemaking; that is, their "proactive engagement in understanding the world by generating, using, and extending scientific knowledge in communities" (Schwarz et al, 2017, p. 6). In such environments, students take up modeling for purposes such as explanation and prediction, making and discussing choices about what to include and how to represent it in light of epistemic goals. They identify, coordinate, and evaluate elements and relationships that can explain phenomena (Braaten & Windschitl, 2011; Krist et al., 2019; Schwarz et al, 2009), Further, because sensemaking involves identifying and addressing gaps in reasoning, students work with models to articulate puzzles and problems for the class to address (Phillips et al., 2017). They engage with each other's ideas—questioning modelers' choices and intent and disagreeing with or taking up ideas in models (Ford & Forman, 2008; Kelly et al., 2008; Passmore & Svoboda, 2012). And finally, they treat models as tentative, with students revising their ideas and representations by considering new evidence and ideas (Passmore et al., 2009; Schwarz et al., 2009).

We still have much to learn about how to instantiate these sensemaking activities in classrooms. Often, students and teachers take up models as placeholders for scientific constructs or as complete representations of canonical ideas (Guy-Gaytán et al., 2019). Teachers may emphasize model construction over model use or revision, treating models as pre-assessments and ways to represent final understandings of phenomena (Gouvea & Passmore, 2017; Khan, 2011; Vo et al., 2019). Further, students can see models as complete renderings, rather than as partial representations constructed in light of a goal (Passmore et al., 2014). They may perceive classroom modeling as concerned with demonstrating a “correct” answer or completing a task to show what you know (Ke & Schwarz, 2021). They may also need support to see how models can support predictions and be revised considering new data (Schwarz et al., 2009).

An additional need is better understanding how students make conceptual progress *through* modeling. Most evidence that modeling supports conceptual progress is presented in comparisons of pre- and post-understandings of phenomena, using students’ model-based explanations or comparisons of learning in classrooms that did and did not take model-based approaches (Baumfalk et al., 2019; Samarapungavan et al., 2017; Schwarz et al., 2009; Zangori et al., 2017). Descriptions have typically emphasized how initial models situate inquiry and what understandings students’ final models demonstrate. There has been less attention to exactly *how* modeling activity supports conceptual work. From a *models for* perspective, this issue is of central importance. If students and teachers don’t experience models as contributing to their sensemaking and as supporting conceptual progress, why would they take them up as tools to reason with and about?

Models as Co-Participants in Classroom Sensemaking

The first principle we explore is *that models can do work, acting as co-participants in classroom sensemaking*. This is an emerging perspective that could more explicitly guide classroom design. Scholars have called for understanding modeling as discursive, embodied, and perspectival (Sengupta et al., 2018). Pierson et al. (2020) described the range of productive stances students might take toward computational models: as conversational peers, co-constructors of inquiry, and projections of students' agency and identity. Other authors have emphasized how models can provide resistance that pushes back on students' ideas, prompting argumentation and supporting revision of models and ideas (e.g., Hardy et al., 2020; Manz, 2015).

As an example of models doing work, consider Tobin et al.'s (2018) description of how working with an established "cubes" model of energy flow supported fourth-grade students to engage in argumentation and "discover" a new form of energy. As they modeled a system that included a solar cell, the students found that the sun's energy needed to be represented to meet the requirements of the cubes system, but did not fit into their established categories (motion, elastic, thermal, electrical). From our point of view, the solar cell system and the energy cubes model pushed back on, or resisted, each other. The energy cubes system provided a framework of transformation across energy kind that the solar cell system both did fit (it showed energy transformation; there was heat involved) and did not fit (it was unclear if the sun's heat was important; it demanded a new form of energy, there was a contininous flow). The model prompted specific questions about components, transfer, and conservation, initiating cycles of model revision as the solar cell system resisted the initial model. The energy cubes model and solar cell system participated *with* children, supporting joint activity and conceptual progress.

This example is consistent with a perspective on modeling as a dance of agency, where models do work alongside modelers by providing resources and resistances that support progress. To be clear, we are not advocating that models do *all* the work, which might look a lot like providing young people with canonical models as representations of phenomena that they should adopt. However, we suggest that it is useful to take a design and analysis perspective that asks how particular model forms and resources contribute to sensemaking. This perspective involves making design conjectures about how modeling might support sensemaking and where modeling can push back on students' ideas and elicit puzzles. After embodying these conjectures in design, we can examine how students engage in cycles of model-based problem-solving and understand how different representations supported problem formation and sensemaking.

Interlocking Models

A second principle is that a useful design move is to engage students in seeking to interlock, or relate, multiple models. This principle is rooted in the work of philosophers and sociologists of science who emphasize modeling as the work of developing, aligning, and stabilizing model systems, rather than the construction and revision of individual models (Cartwright, 1999; Nersessian, 2008; Rheinberger, 2015; Rouse, 2015). From this perspective, models do work *in relation to each other* as investigators seek to align partial renderings of a phenomenon in a model system that supports explanation.

Research has begun to explore students working with multiple models in instruction (e.g., Bielik et al., 2021; Blikstein et al., 2016; Gouvea & Wagh, 2018; Ke et al., 2021; Lehrer & Schauble, 2012; Pierson et al., 2021). These can include descriptive models, explanatory or mechanistic models, systems models, simulations, data representations, and empirical investigations, among others. For example, one instructional design for high school biology students (Ke et al., 2021; Elsner et al., 2023) used a multiple models approach to help students understand how interventions such as hand-washing and masking can prevent viral spread. Students initially created descriptive models of coronavirus and soap molecules to describe their molecular structures, then developed mechanistic models that showed how soap interacted with lipids to explain the utility of handwashing. They then used simulations to explore the effect of distancing and mathematical models to understand exponential viral spread given different reproduction rates. This research has suggested that different model forms support students to attend to different entities and relations, and further, that students can layer the learnings from one model onto another to deepen their understanding (Bielik et al, 2021.; Danish et al., 2020; Wilkerson et al., 2015).

Researchers have also sought to better understand the mechanisms by which working across models supports learning. Research on bifocal modeling (Blikstein et al., 2016; Fuhrmann et al., 2018) has demonstrated how moving between empirical investigations and computational models can allow high school students to recognize discrepancies or contradictions, supporting them to pose new questions and refine computational models. Gouvea and Wagh (2018) have supported university students studying bacterial mutation to work across empirical (E coli in growth media) and computational representations, showing how students drew on, and sought to reconcile, information from both systems at all stages of investigation (planning, theorizing, model evaluation). For example, as students sought to develop a question to investigate empirically, and struggled with the idea that their question was “too vague,” they used the simulation to explore possible outcomes and to identify limitations in its assumptions and inputs, thus prompting a more specific question for their dish (empirical) investigation.

This research is relatively new and has not typically been used to guide instruction in elementary school and middle school classrooms. More work is needed to understand how to develop and connect sequences of modeling work (Bielik et al, 2021; Ke et al., 2021). In addition, questions remain as to how to support students to recognize models as bearing on each other and what it might look like, from students' points of view, for models to interlock. Gouvea and Wagh (2018) noted that they selected the case of a group who treated the systems as related and that not all student groups worked with the systems in this way. Elsner et al (2023) noted that students needed substantial support to make connections across different models.

Interlocking Supports Fine-Grained Conceptual Progress

A final principle is the need to attune both design and analysis to fine-grained conceptual progress in modeling work. We draw from Hammer and colleagues (2005) in using resources as a unit of analysis, focusing on how students see and use aspects of disciplinary concepts for particular purposes. Further, we draw from situative perspectives that describe learning as changes in ways of navigating and using the resources in different contexts, locating cognition as a relation between the person and environment (Greeno & Hall, 2008; Hutchins, 1995). This is consistent with a conceptualization of modeling as distributed across people, materials, and representations (Nersessian, 2003). Nersessian (2008, 2012) describes conceptual progress as occurring through cycles of problem-solving at the junctures between models. Moving between and seeking to relate models serves as a context to make decisions about what is important, surface differences, and engage in model evaluation.

Drawing from these ideas, we suspect that moments where students interlock models, bringing them into relation to each other, can be powerful for conceptual work. We apply this perspective in design by examining the “conceptual terrain” of phenomena and target explanations. Specifically, we make conjectures about what aspects of phenomena need to be made visible and connected in explanations for students to make progress on understanding the phenomenon. We then consider how particular representations, and movement between these representations, might support students seeing ideas as relevant, differentiating ideas or attributes, developing explanatory mechanisms, and making connections (Manz, 2015; Wilkerson et al., 2015).

Study Overview

It is critical that students experience modeling as a meaningful and generative practice from their earliest classroom experiences (NASEM, 2022). Previous work shows that this undertaking is challenging and underlines the need for further research on designs for classroom modeling and fine-grained descriptions of what sensemaking with models can look like in the elementary grades. This study seeks to contribute to the literature by exploring classroom design that involves young students in working across and relating models.

To this end, we worked with teachers to co-design a modeling experience for fifth-grade students (ages 10-11) within a content area (conservation of matter across phase change) where no one model would be sufficient for conceptual progress. We developed an instructional sequence in which students worked with pen-and-paper models, simulations, empirical models, and data representations. We conjectured that engaging students in relating models to each other could allow models to do work alongside students, supporting interactions where students made conceptual progress through sensemaking with models, e.g., considering models’ implications, developing problems and puzzles, and engaging with each other's ideas. Specifically, we sought to understand:

1. What work can models do for young people as they (the models) interlock in classroom activity?
2. How can interlocking models support classroom interactions characterized by sensemaking and conceptual progress?

We addressed our research questions through design-based research (Cobb et al, 2003), partnering with classroom teachers in co-design (Penuel et al, 2007). Over three years, we examined existing materials, made conjectures about how to adapt materials to engage students in more robust modeling experiences that drew on the ideas above, tested ideas together, analyzed data in light of our conjectures, and re-designed and re-implemented the sequence in iterative cycles.

Context

This work took place within a multi-year co-design partnership with a public school district in the Northeast United States. The focus of the partnership was adapting curriculum and developing elementary teachers' practice, with a focus on supporting children's sensemaking, investigation, and modeling. Within this larger partnership, the research team had funding to work with second and fifth grade teachers to develop, test, and support science investigations that centered modeling.

The district was in its third year of implementing curriculum and professional learning at the time that the study began. They used phenomena-based units adapted for district use from various sources (NGSS Storylines, ML-PBL) or written by teacher-leaders, anchoring units in events and processes to elicit tentative explanations and establish a need for investigation (Reiser et al., 2021). Further, district units emphasized the development of a storyline that is coherent from students' point of view, where students see their investigations as useful for making progress on their questions (Penuel & Reiser, 2018; Schwarz et al., 2017). Finally, the district emphasized modeling as a key practice in fifth grade. This was the initial grade in the district's elementary sequence that modeling received such emphasis, though earlier grades used modeling as students sought to understand force, energy, and landforms.

We worked closely with two teachers (Ms. Shaw and Ms. Lily) to co-design and implement modeling activity. Both had taught for more than eight years when the study began. They had been selected as teacher-leaders for the larger district effort, then became interested in the funded co-design project focused on modeling and investigation. The students in the district are culturally and linguistically diverse: approximately 40% identify as Hispanic, 40% as White, 10% as Asian, and 5% as Black or African American. Ms. Shaw's school was largely representative of district demographics, with 55% of students speaking a language other than English at home and 70% designated by state criteria as "low income," (families making up to 185% of the federal poverty level standard). She typically taught 20-24 students in each of two blocks of science. Ms. Lily's class was designated by the district as a Sheltered English Immersion (SEI) classroom and was composed of 15-18 emerging multilingual students, most of whom speaking Spanish or Portuguese at home. Teachers and researchers identified as white and of European descent and varied in our Spanish linguistic proficiency but spoke little Portuguese. As language practices in the state and district shifted toward supporting multilingualism, Ms. Lily and her Spanish and Portuguese speaking aides increasingly posted directions in multiple languages and supported students to use multiple languages and translate across languages.

We drew on co-design principles and norms to support joint learning (Manz, Heredia, Allen, and Penuel, 2022; Penuel et al., 2007). Specifically, we sought to value all participants' expertise, use tools and routines to jointly establish goals and refine designs, and establish different roles and responsibilities for participants but make use of hybrid roles as possible. Designs were co-developed by researchers and teachers, with researchers contributing research-based ideas about modeling, students' challenges with modeling, and particle descriptions of matter, and teachers contributing their past experiences and challenges teaching the unit. Researchers and teachers shared responsibility for developing lesson plans, student sheets, and other instructional materials. Teachers implemented lessons in classrooms, but researchers sometimes acted as co-teachers by posing questions, working with student groups, and occasionally teaching lessons. Researchers took on a larger role in data analysis (for example, logging data, developing coding schemes, analyzing a greater proportion of the data). However, teachers were involved in data analysis by providing feedback on foci and coding schemes and participating in analysis during after-school and multi-day summer meetings.

Design of the Instructional Sequence

The design addressed fifth-grade Next Generation Science Standards (NGSS) performance expectations related to matter and its interactions, including adaptations made by the state:

(1) "Measure and graph quantities to provide evidence that regardless of the type of change that occurs when heating, cooling, or mixing substances, the total weight of matter is conserved." (NGSS)

(2) "Develop a model to describe that matter is made of particles too small to be seen." (NGSS)

(3) "Use a particle model to explain common phenomena involving gases and phase changes." (State standard)

These standards are often addressed by engaging students with phase changes in water, as the only common substance existing in all three phases at temperatures possible in a classroom. Students might develop particle models that show how the movement and spacing of water particles can explain observable phenomena such as water becoming hard as it freezes, weighing the same after freezing, “disappearing” as it evaporates, or appearing on the outside of cans taken from the fridge (Jaber & Hammer, 2016; Kenyon et al., 2008; Wiser et al, 2012). Typical empirical work includes weighing water in closed systems before and after phase change, adding air to balloons to demonstrate it has weight, or using humidity monitors to measure if there is gaseous water in the air. Further, instructional sequences often use simulations to help students visualize and explore the speed and spacing of particles.

A central modeling challenge is helping students relate micro-level entities (particles or molecules) with macro-level, observable changes in the behavior or appearance of a substance, establishing coherence across scalar levels for the purposes of explanation (Krist et al, 2019; Stevens et al, 2010). For example, consider the idea that as water freezes it expands but does not weigh more. At the *observable* level, students have to notice and wonder about changes in size, differentiate attributes (e.g., weight, volume, height), and interpret data about volume and weight change that is likely to be full of variability and error. Previous research has demonstrated the challenges learners face in these areas (Lehrer & Schauble, 2000; Lehrer et al., 2020; Wiser et al., 2012, Smith et al, 2006). Further, learners face difficulties using *micro-level* particle models to explain observable qualities of matter. They can conceive of particles as in a substance rather than making up a substance (Merritt & Krajcik, 2013) and as inheriting observable properties of the material, e.g., that solid water particles are frozen or unmoving (Johnson & Papageorgiou, 2009; Talanquer, 2009). Ideas central to using molecules to explain phase change can also be non-intuitive, such as empty space between molecules or using the same particles behaving or arranging differently (Gilbert & Treagust, 2009; Paik et al., 2004).

In their initial design, the district had drawn from a variety of materials and developed a sequence in which students were introduced to the particle model of matter and used pen-and-paper models to explain the dispersal of food coloring in different temperatures of water, differences between ice and water, and the phenomenon of water evaporating from the dye jars. Students examined the dye dispersal phenomenon and explored particle models of liquids moving and mixing, worked with a simulation (PhET™, University of Colorado, Boulder[i]) that showed particle movement at different temperatures, then constructed a joint explanatory model of dye dispersal. They were then asked to think about what happens at colder and warmer temperatures, leading to experiences in which students explored phase change and the conservation of matter, including freezing water and oil, making sense of water evaporating, and adding air to balloons to demonstrate that air has weight. Throughout, students made and revised pen-and-paper models in which they used particles to explain observations.

As we began our work together, the design team, including teachers, first unpacked the standards using the research literature, teachers' prior experience, and a project protocol for considering models and their relations from students' perspectives. We sought to understand which ideas described in the standards might be challenging for students and what resources they might bring to different phenomena and representational systems[ii] (e.g. pen-and-paper models explaining different phenomena, simulations, empirical representations of water changing state such as freezing water in vials or evaporating water in closed and open systems, data representations). The research team contributed ideas from previous research, while the teachers brought their experience from the unit and other investigations. We then made conjectures about how specific modeling activities (e.g., using simulations, empirical representations, data representations) might support students to work through the ideas we had unpacked. We considered how students might move between and relate models (e.g., using a simulation to examine questions coming up from an empirical model of water freezing) in ways that could provide resources, support argumentation, or pose puzzles to situate further exploration.

Through this process, we came to focus our work on one part of the unit, where students explore water changing phase from a liquid to a solid. Our redesigned modeling sequence (Table 1) engaged students with the phenomenon of a glass bottle filled with water freezing and breaking. We planned for students to develop initial pen-and-paper models to explain the phenomenon, then engage in an empirical investigation of weight and volume. We hope that this work would establish a need to revise their models to account for and explain the finding as water freezes it hardens and expands but does not weigh more. In the following paragraphs, we explain the design that we developed as it was enacted by Ms. Lily in 2020, describing (1) the representational systems students engaged with, (2) conjectured opportunities for developing and interlocking models, (3) how the design was meant to address the challenges and opportunities the design team had identified, including our understanding of the conceptual terrain students needed to navigate.[iii]

Ms. Lily began the sequence by introducing a video of the glass bottle filled with water exploding, using it as an anchoring phenomenon. We conjectured that the video would provide an observable representation of water expanding as it freezes (as it places pressure on its container) and would serve as a context to return to over the course of students' work. Students shared tentative explanations and developed *pencil-and-paper models*. We conjectured that they would draw on resources from representations of liquid particles and temperature used earlier in the unit, including the PhET simulation, which shows molecules slowing down and coming together as temperature decreases. This provided an early opportunity for different models to interlock in students' thinking and discussion.

After students developed pen-and-paper models, the teacher selected student models for class discussion, looking for models that called on different resources (e.g., one student model that showed molecules coming together based on earlier experiences with the simulation and class consensus model, another that showed molecules growing or moving apart to put pressure on the bottle as seen in the video). We hoped that students would see consequential differences in each other's models and pose questions. We conjectured that the teacher could help students highlight observable qualities like volume, height, and weight, helping them to differentiate these attributes and consider how molecular movement and positioning might relate to them. We further hoped that this work would seed student disagreement about whether weight and volume change as water freezes, establishing a need for empirical investigation.

After developing questions about weight and volume, the teacher introduced the possibility of further investigation using plastic vials with water level markings. Students discussed how to use the vials to figure out if water expands as it freezes and changes weight as it freezes. They collected individual data before and after freezing (18 vials in Ms. Lily's class). We conjectured that this *empirical model* would provide a shared representation that could stabilize ideas about weight and volume. This was a move to interlock an empirical investigation with an observable phenomenon (the bottle breaking) and with students' pen-and-paper models, which made questions about the observable features of volume, height, and weight visible. For example, developing the empirical model could prompt questions about whether the material and cap of the vials mattered, whether to compare frozen and liquid water side by side or do a before and after comparison, and how to measure weight.

In the next phase of activity, we engaged students with developing *data models* by combining the data from their individual vials. Children (and adults) often interpret small fluctuations in data as supporting their expectations (Chinn & Malhotra 2002; Lehrer et al., 2020). In their previous work, teachers had found it difficult to support conversations about the conversation of matter using water and oil frozen in vials or balloons filled with air, because students attended to individual data points rather than trends and teachers struggled to support them to make sense of the meaning of small changes. We introduced a data table showing each vial with volume before and after freezing, plus weight before and after freezing. We supported conversations about whether students could make claims about whether water changes in size and weight as it freezes. While volume typically clearly increases, weight tends to vary and requires counting or re-organizing data, and sometimes deciding to increase precision by re-testing vials. We then asked students to develop a claim about the weight of water and to work with the data to support their claim, a move which we hoped would support them to begin to think about what “most of the data” showed and raise explicit conversations about how to make sense of data and agree on a claim in light of variability.

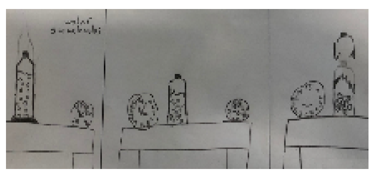
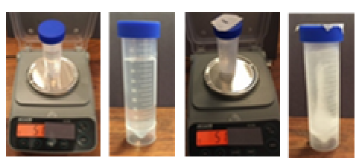
Students next returned to their *pencil-and-paper models* to revise their initial models of the bottle breaking phenomenon. Here, we hoped to support them to revise their models based on a shared understanding that water expands but does not change in weight as it freezes. We also expected that they would lack some resources necessary to use molecules to make sense of how water could expand but not freeze. We were curious about how to support questions and further puzzles as students brought their explanatory molecular models into contact with the empirical model (vials) and its results.

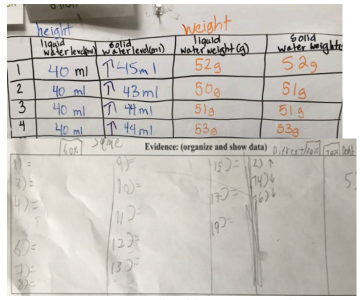
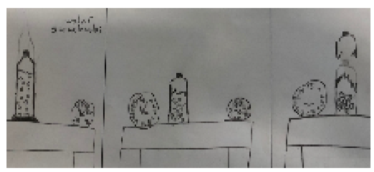
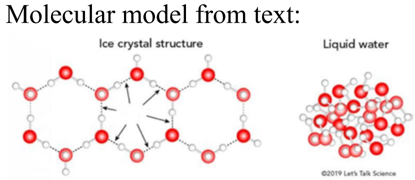
We therefore planned opportunities for students to explore canonical representations of phase change and interlock those with their empirical model and pen-and-paper models. We had used *the PhET simulation* earlier during the dye dispersal work to illustrate particle movement and explore how temperature influenced the speed of molecules. We had found that knowing what to pay attention to in the simulation isn't obvious. The simulation highlights the position and movement of molecules and keeps the number of molecules consistent across phase change (which some simulations don't). But it does not represent the shape and space that that the substance takes up in ways that are particularly easy for students to observe. Further, because it represents the randomness of molecular movement using a small number of molecules, it can be hard for students to interpret. We hoped that students' empirical findings and puzzles could interlock with the simulation to support focus on the number and position of molecules.

Further, we were interested in how students would make sense of canonical models and incorporate them in explanations. While Ms. Lily was unable to complete this part of the sequence due to interruptions from Covid-19, the plan was that she would introduce the law of conservation of matter and a text explaining the unique properties of water as tools to think with and to apply to other experiences with materials changing form and appearance. We hoped that these resources would support students to explain ideas developed through model revision and the simulation. At this point, the teacher could support students to build a class consensus model that incorporated ideas developed through the different representational systems.

Table 1.

Design and Representational Systems

Phase Activity	Image of representational systems introduced or focused on; Conjectures about representational features	Conjectured opportunities for interlocking
Glass bottle breaking (2 days) Students watch a video of phenomenon, offer explanations	 Replayable macro-level representation Elicits ideas about pressure, water expansion, and wider array of explanatory mechanisms.	The video can serve as a context to situate shared modeling work and to return to over time. The video provides material/perceptual resources that may or may not be useful in other models (material, cap, shape).
Initial models (2 days) Students individually construct models. The teacher selects and shares models that differ in molecules' positioning & movement. The class discusses what it means for water to "get bigger," and whether they think water expands in volume and weight as it freezes.	 Student-generated micro- and macro-level representation. Flexible space to propose tentative explanations, share ideas, and revise their thinking.	Students might bring together resources from multiple representational systems (video, simulation, past consensus models, experience) in these models.
Planning vials investigation (2 days) S's are introduced to the vial system and discuss how to use it to understand if the weight and volume of water changes as it freezes.	 Draws attention to and allows students to work with measures of weight and volume (water level). Supports comparison of weight and volume across phase change.	Students redescribe bottle breaking phenomenon, highlighting some features (change before and after due to temperature) and hiding others (material of bottle, explosion, breaking). Provides observable and measurable attributes and evidence that can support a return to the pen-and-paper models and focus work with the simulation.
Enacting the vials investigation (3 days) Students individually fill, weigh, and freeze vials, recording the weight and water level before freezing. They make predictions and discuss variability in initial weights, freeze the vials, and record new data.		

Organizing and making a claim from vials data (3 days) Students examine a data table showing all vials. They reorganize the data and use it to support a claim. They compare representations and make the claim that as water freezes, it expands but does not weigh more.	 Represents and allows students to work with many data points; moving beyond their vials to "what most of the vials did." Context for making sense of variation in data and considering how to make a claim in light of variability.	The emerging claim (that freezing water expands but weight stays the same) supports model revision and the development of puzzles (how can this be) to focus modeling work.
Return to initial models and pose new questions (1-2 days) Students explore how their initial models and (if necessary) an outrageous model showing molecules multiplying are/aren't consistent with the investigation results.	 (See above)	Returning to revise these models can allow students to interlock resources from different models in new ways and prompt new questions and need for new resources.
Use simulation to make progress on questions (2 days) Students use the simulation to make sense of how water molecules behave as water freezes.	 Micro-level molecular representation of phase change. Highlights how same number of molecules move and arrange as temperature changes. Does not show shape or macroscopic features of substance.	Can provide a way to test students' questions about whether the number of molecules stays constant and how molecules can take up more space without weighing more. Questions from previous work can focus activity with the simulation, which otherwise can be broad and unfocused.
Connect to canonical ideas and develop consensus model (3 days) Students engage with the the law of conservation of matter and a text on water. They develop a joint consensus model.	Molecular model from text: 	Can be interlocked with students' puzzles about weight and their progress on the simulation to stabilize and deepen both molecular and observable descriptions of matter.

Methods

In this section, we describe our processes for implementing, collecting data on, and revising the design. We then describe our analytic work to address the two research questions: *What work can models do for young people as they (the models) interlock in classroom activity? How can interlocking models support classroom interactions characterized by sensemaking and conceptual progress?*

Design Implementation and Revision

Ms. Shaw implemented a version of the design described above in Fall, 2019 with two fifth grade classes while Ms. Lily implemented in January-March, 2020. Each implemented the design again in Fall, 2021.[iv] We collected audio, video, and student artifacts and fieldnotes for lessons, which were typically 45 minutes in length, and ranged from 15-20 lessons. We revised the design between each implementation, with both teachers and researchers participating in analysis and revision as described previously.

Our analysis of each implementation focused on (1) clarifying how students navigated the conceptual terrain, (2) understanding how students were taking up resources in and across models to make conceptual progress, and (3) documenting disagreements, puzzles, and challenges. We reviewed field notes, student work, and video of selected episodes for each phase of activity (Table 1). In addition, we developed and reviewed content logs for all video for the first two implementations (Fall, 2019 and Spring, 2020). In these logs, we recorded the structure of activity (e.g., purpose-setting, whole class sensemaking, small group work) and focal question or problem under consideration (either introduced by the teacher or a student). For each focal question (typically lasting 30 seconds to 4 minutes), we noted the models referenced; the ideas about expansion, weight, and molecules at play; and the ways students were engaging with or questioning models. We developed summaries of the ways that models were developed, used, and related. To understand the conceptual terrain, we engaged in a fine-grained analysis of student ideas. These included the observable features students attended to (volume, water level, weight, hardness of ice, the features of the bottle), the aspects of molecules (number, position, movement), and mechanisms such as pressure, temperature, and energy (see supplemental materials, Table 2 for a full description). Finally, we described opportunities and challenges and noted potential revisions to better support engage in sensemaking with models, relate models, and use models to support conceptual progress.

During the initial analysis of Ms. Shaw's and Ms. Lily's first implementation, we became became increasingly attuned to how models were doing work in classroom conversations. We became interested in the research questions described in the introduction and sought to better understand what forms of work the models were doing when brought into contact and how these forms of work supported students' sensemaking and conceptual progress.

Analytic Methods for Addressing Research Questions

We addressed the two research questions through a close analysis of the second implementation in Ms. Lily's classroom (Spring, 2020), followed by triangulation with findings from other iterations. Focusing on one classroom's trajectory allowed us to track conceptual progress, making links between ideas and practices generated in interaction, models, and the development of classroom ideas over time. To ground our analysis of Ms. Lily's implementation, we used the content logs to identify whole-group activity where students were discussing the phenomenon while working with a model and/or bringing ideas from multiple models to bear on each other. We identified 16 episodes from the 17 days of instruction, ranging in length from 8 minutes to 30 minutes, with multiple episodes from some days of instruction and none from others. Spanish or Portuguese speech in these episodes were transcribed and translated to English. Then, using an interaction analytic approach (Hall & Stevens, 2015), we moved back and forth between video, transcript, and conjectures, testing and refining conjectures across episodes, and then, at a larger grain size, across iterations.

Our first analytic pass focused on describing and relating (1) the representations students drew on and the way they brought representations into relation with each other and (2) conceptual resources and/or progress. To identify *conceptual resources*, we drew on and refined the conceptual terrain (Supplemental Materials, Table 1). We operationalized *conceptual progress* as seeing a new idea as important, differentiating ideas, connecting ideas, drawing on ideas for explanatory purposes, and/or stabilizing ideas across community members and time. We oriented analysis toward the following questions: *What resources for water expansion and phase change were surfaced, connected, and/or refined? What role did representations play in conceptual progress? Do we see evidence of interlocking models and how? What forms of work are visible as models interlock?* We segmented transcripts into chunks of activity focused on a particular question or statement posed by a teacher or student, then analyzed talk, gesture, and work with representations. We tracked and refined conjectures across the sixteen episodes.

This analysis supported us in several ways. First, it helped us refine the conceptual terrain and see where different models supported conceptual progress. Second, it helped us describe what it looked like for students to take up models *for sensemaking* and make connections to other literature to develop indicators of modeling for sensemaking (Table 2). Finally, it helped us answer our first research question, as we identified four *forms of work* that we saw interlocking models contributing to students' sensemaking: *contradictions, gaps, constraints, and representational surplus.* Consistent with methods for iterative qualitative analysis (Gee &

Green, 1998) we strengthened our thinking about these forms of work by moving between the data and the literature. We developed detailed descriptions of the four forms of work and how they appeared to support sensemaking and conceptual progress (see Findings).

Table 2

Sensemaking Indicators Used in Analysis

Construct	Description	Indicators
Using models to articulate or figure out how and why phenomena occur	Identifying and reasoning about entities and relationships that explain observable phenomena or processes (Ke et al., 2021; Krist et al., 2019; Schwarz et al, 2009)	- Students make use of models to explain, predict, or figure something out. - Students link specific choices in models to how they help them explain, predict, or figure something out about a phenomenon. - Students draw on models to connect and coordinate molecular positioning, movement, etc to observable features of water expansion (e.g., volume, weight).
Engage with models' implications	Evaluating models based on their implications, by (a) following through on the implications of relationships in models to evaluate whether those models can explain a phenomenon and (b) considering how models predict and explain phenomena for which they were not developed (Berland et al., 2016; Passmore et al, 2009; Schwarz et al., 2009)	- Students use models to engage in "if, then" thinking. - Students link specific aspects of models to their implications for observable features as they agree or disagree with a model. - Students propose new phenomena that models could be applied to.
Problematize and articulate puzzles for community to address	Using models to develop puzzles and questions important for their own, and the community's, further inquiry into a phenomenon (Phillips et al., 2017; Odden & Russ, 2018)	- Students experience and seek to articulate dissatisfaction with explanations and/or models in their work with models. - Students use models to pose new questions for the class to address,
Engage with others' ideas	Engaging with modeling as part of the social construction of knowledge, including: seeking to understand modelers' choices and intent; bringing new evidence to bear to disagree with or proposing refinements to models; taking up new ideas from others' models. (Schwarz et al, 2009; Kelly et al., 2008; Berland et al, 2016; Passmore & Svoboda, 2011).	- Students agree and disagree with ideas in others' models. - Students take up ideas from others in their explanations. - Student conversation is connected, rather than sharing one idea after another.
Treat models as tentative and revisable	Revising ideas and representations based on new evidence and ideas (Passmore et al., 2009; Schwarz et al., 2009).	-Students indicate they disagree with their previous model -Students propose a change to their model.

We then selected two days of instruction for further analysis. One was when students shared *initial models* of the bottle breaking, drawing on resources from the video of the phenomenon and previous models. The second occurred near the end of the sequence, when students *returned to examine their initial models in light of the findings from the vial investigation*. These were pivotal days because they represented the places in the sequence where students had the greatest opportunity to bring multiple models to bear on each other. Further, they provided an interesting contrast, because there were substantially different models (and therefore resources) to interlock, though students were examining the same pen-and-paper models.

We analyzed all episodes within these two days (five, each focused on discussing one pen-and-paper model). We sought to both refine our findings in relation to our first research question and to address our second question—to understand the interaction between the work that models were doing and students' modeling activity. We re-analyzed these episodes, exploring (1) what representations were interlocking, (2) how contradictions, gaps, constraints, and/or representational surplus emerged and influenced activity, and (3) how students were taking up models for sensemaking and making conceptual progress. Finally, we triangulated these findings with reviews of content logs, field notes, and reflections for all iterations, seeking to understand if there was evidence that these forms of work and how they supported student modeling and conceptual progress were consistent across teachers and implementations.

Findings

In this section, we share what we have learned about how interlocking models can contribute to students' sensemaking and conceptual progress. As we exemplify in the episode analyses, students were often initially unsure sure how to connect resources from different representational systems. They focused on different aspects of the phenomenon (why water hardens, why water expands, the role of air), brought different representational resources to bear, and questioned how aspects of the phenomenon (the materials of the bottle, the weight of water) needed to be represented in new models. As they worked together to relate models, they engaged in sensemaking—asking mechanistic questions, considering the implications of models, and working with each other's ideas.

Our analysis helped us see four forms of work that models contributed when brought into contact with each other. We do not claim that these are the only forms of work that models can do. Nor do we claim that they are entirely separate; as we describe below, they were often entangled with each other. We present these four forms of work because they have been useful to us for understanding how and when students engage in sensemaking and make conceptual progress as they bring models in relation to each other. They have also proved useful for understanding how teachers can invite and amplify models' co-participation in classroom sensemaking. We briefly summarize them here, then expand our description using three focal episodes.

One form of work was for interlocking models to provide *contradictions* as resources that seemed in tension were brought into contact from different models. Working with contradictions appeared to support students to play out the implications of models and current explanations. Another form of work was to provide *constraints,* where one model system could articulate a "must-have" for another, focusing modeling activity. A third form of work was *representational surplus* (Hesse, 1960; Nersessian, 2008), where representations brought with them meanings and implications the modeler might not fully interrogate until put in contact with another model, making new resources visible or provoking new questions. Finally, and often in conjunction with contradictions, constraints, or representational surplus, we saw interlocking models providing *gaps* for students to work to address; that is, making visible places where current understandings weren't yet sufficient and/or resources across models could not yet be brought into satisfying relation, in turn, provoking puzzles and focusing further activity.

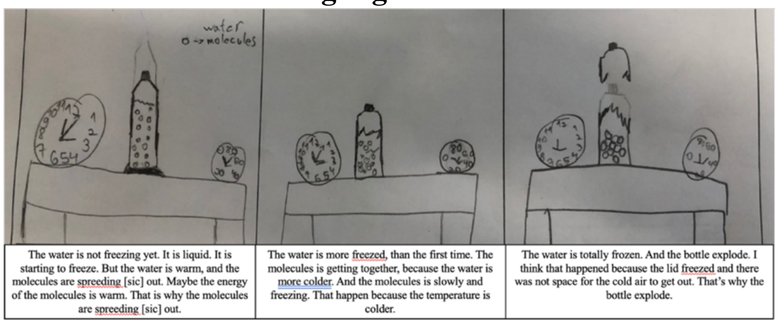
Contradictions & Gaps in Early Modeling Work

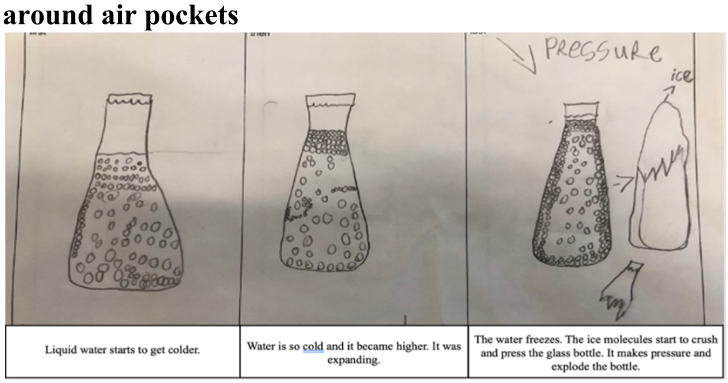
Contradictions are one form of work that models can contribute. One reoccurring contradiction we saw across implementations was between molecular understandings of water cooling drawn from earlier models (molecules slowing down and coming together) and the need for a mechanism of pressure for the bottle breaking. Across iterations, we found that this contradiction could support students to compare models and examine models' implications. Further, it appeared that contradictions helped make visible gaps occurring as students brought resources together, attuning students to mechanistic questions.

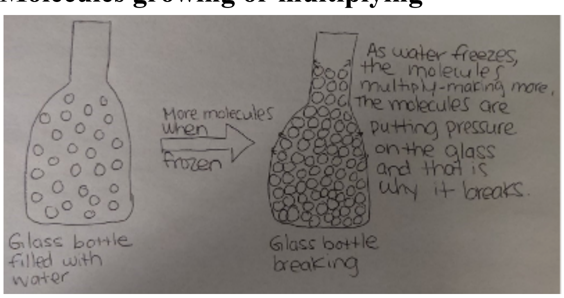
The initial class discussion of Rafael's model illustrates how contradictions and gaps supported students' sensemaking and conceptual progress. The discussion took place in the first days of instruction, as students considered models of why the glass bottle broke (Table 1). In Ms. Lily's class, consistent with other implementations, students produced a variety of initial models that drew on different resources from students' experience, the bottle breaking video, students' previous experience with the simulation, and earlier models of hot and cold water (Table 3). Rafael (row 1), like several other students in this classroom (and across different implementations), drew from earlier models the idea that as water cools, molecules slow down and come together, drawing molecules packing together as water become solid. He did not match the molecules with the water's edge and did not show water expanding. He did not acknowledge a tension in how water molecules coming together could lead to explosion; instead, in his last frame, he focused on another mechanism for the bottle exploding, conjecturing that the lid of the bottle froze, trapping air and thus causing pressure. We selected this model for discussion because we were curious if other students, particularly those who had focused on using molecules to provide pressure, would recognize tensions in the resources being brought together.

Table 3.

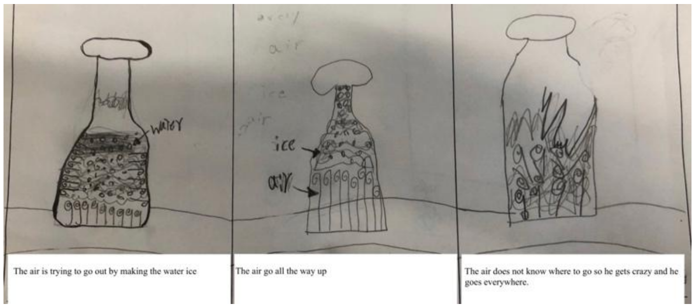
Initial Model Types and Frequency in Ms. Lily's Class

<table>
<tr><th>Focus and Example Model</th><th>Characteristics</th><th>Frequency (Ms. Lilys class; n=16)</th></tr>
<tr><td>Water molecules coming together
</td><td>Water molecules coming together as water cools and freezes.

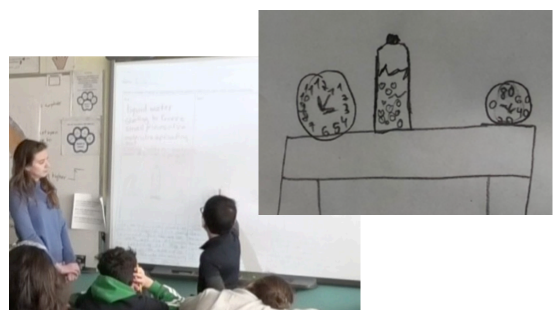
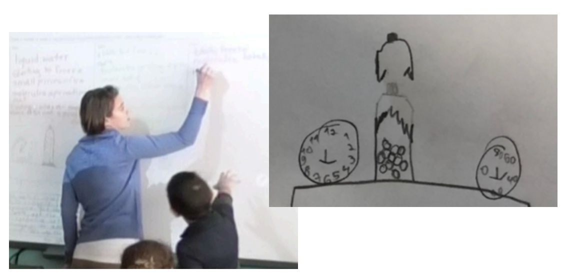
Often connected to previous work with simulation and dye and/or explaining solids as hard.</td><td>5</td></tr>
<tr><td>Water molecules moving away from each other or freezing around air pockets
</td><td>Water molecules moving apart as water freezes.

Often connected to pressure on bottle and/or experience of water growing as it freezes.</td><td>5</td></tr>
<tr><td>Molecules growing or multiplying
</td><td>Water molecules growing or multiplying.

Connected to pressure.</td><td>0 (example generated by teacher; in other classes, sometimes have 1 or 2)</td></tr>
</table>

Other Mechanisms 		Students focus on air, qualities of the bottle, or power of water without using position or movement of water molecules as a mechanism for bottle breaking or qualities of water.	6

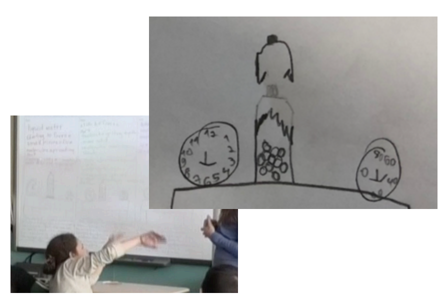
Episode analysis. As Rafael presented his model (Table 3, Row 1), he focused on the molecules slowing down and coming together. He shared that in his first panel the molecules were spreading out and moving fast because the water was warm and they had energy, which Ms. Lily wrote in notes above the model. He then explained the second and third panels.

	Transcript	Parts of models referenced[v]
1	Rafael: The second drawing in here, the water is like a little bit freezed and the molecules is like getting together and like getting solid and the molecules are moving more slowly than the first time and it is like the molecules is freezed or freezing with the ice and the water gets colder…and the temperature gets cold… energy of the molecules gets colder too and that's why they stop (.) they like freeze…	
2	(*Teacher pauses, then asks Rafael to describe the third pane)*	
3	Rafael: In picture number three the water suddenly freeze and the molecules is together like is- like they are mixing and getting just- make and creating another molecule like a bigger one and (.) now here the molecules is totally freezed and I wrote here that (.) and I think that the lid of the bottle freezed and there was no space for the cold water to get out	
4	Ms. Lily: Cold water to get out	
5	Rafael: Yeah and that's why the (.) no the cold air (.) and that's why the ice gets to the side of the bottle- make the bottle explode	

Here, Rafael considered and related ideas about molecular movement and phase change. He drew on resources from prior work (ideas about energy, the movement of molecules, and how close or spread out molecules are). He also made some initial moves to use his model to explain ("that's why they stop;" "that's why the ice gets to the side."). He did not appear to be grappling with the contradiction of molecules coming together and ice expanding. However, we see some markers of recognizing potential gaps in his explanation; namely his use of "suddenly" and self-correction,"no space for the cold water to get out- no the cold air."

After students talked about Rafael's model in partners, Ms. Lily asked them to share. Bertrand said, "Can I say something else. I think that maybe the- you know when the water is turning to ice- that the ice takes more space and the air that's inside the water bottle can't escape." Bertrand indicated that he knew he was adding another idea, rather than directly responding to Rafael's model. He worked with another student over the next three minutes to develop an idea of air inside water making space as water cools down. Like Rafael, they focused on air and water as entities that could cause the bottle to explode. In contrast to Rafael, their conversation focused on perceptual experiences of water expanding but not molecular mechanisms or understandings of phase change.

Ms. Lily then redirected students to ask questions about Rafael's model.

Transcript	Parts of models referenced
1 Casandra: How do the ice gets to the sides in the last one?	
2 Ms. Lily: So how did the ice get to the=	
3 Casandra: =No no no wait (1.0) yeah the ice gets to the side (.) how does it?	
4 Ms. Lily: So where are you looking on here to ask that question?	
5 Casandra: The last one	

6 Ms. Lily: The last one so I actually (.) you and I are thinking the same question (.) so I was going to focus on the last picture as well and I was going to ask about a couple things (.) so Rafael could you answer Casandra's question about how does the ice get to the side (.) how does the ice get to the side.

7 Rafael: It's 'cause the water (.) the water starts like starts on the side and then when the water starts freezing it makes like (.) it gets bigger and it gets spread out (.) and spread out on the side and down.

While in his explanation, Rafael mentioned water needing to get to the sides of the bottle to break it (an idea of pressure that was intuitive for students), he used molecules to show water cooling down and coming together to make a hard substance. Perhaps as a result, the molecules in his last pane didn't touch the edges of the bottle, nor did they extend to where the bottle seemed to break. Here, we find it useful to consider *the model* as holding a contradiction that could support students' activity, even if neither Rafael nor Casandra fully saw or named it. The resources in tension with each other were drawn from earlier models, the bottle breaking phenomenon, and Rafael's rendering of molecule. The tensions provided something for Casandra to probe, thus supporting her to develop a gap between what the model needed to explain (pressure or ice getting to the sides) and how the molecules were represented. This gap, in turn, supported her to pose a mechanistic question using Rafael's model: "How do[es] the ice get to the sides?"

Initial modeling work in units often focuses on helping students articulate what they don't know or agree on to seed further investigation. This episode shows how models acted as co-participants in this process as, in interlocking, they provided contradictions and gaps that supported students to take up model implications and articulate questions. The resources provided by previous models of water cooling (suggesting that molecules should slow down and come together) were brought into contact with the features of the bottle breaking video, leading to an implicit contradiction in Rafael's model. The contradiction wasn't articulated by Rafael, nor was it ever fully articulated by students; yet nonetheless, it appeared to *do work*, in that it presented students with a set of resources that didn't fit seamlessly, which supported them to follow through on the implications of representational choices, leading to gaps they could work with. These gaps in turn, supported mechanistic questions, such as how the ice could get to the sides, and (later in the conversation) how multiple molecules coming together could make one big molecule or how the water turned to ice. In discussing these questions, students began to articulate partial explanations and mechanisms for different aspects of the phenomenon (what molecules are doing to make the water solid, what would make the bottle break, what it means to "get bigger"). In turn, Ms. Lily was able to use these questions to anchor further discussion and activity.

Contradictions in early modeling across implementations. Across implementations, individual students' initial modeling has tended to orient to one aspect of the phenomenon under study: most often, properties of frozen materials such as hardness, ice putting pressure on the bottle, or ice expanding. Students draw on conventions and ideas from previous modeling work (and other experiences) to try to explain *their* focal aspect. These early representations involve implicit tensions that *other* students (focusing on another aspect of the phenomenon) can see and engage with. Discussion can support students to follow through on the implications of models, develop puzzles for further work, and explore what might count as a satisfying explanation. Across implementations, these conversations have benefitted from teachers directing students back to the model under discussion, naming different ideas and articulating from where students are drawing them, and orienting to contradictions and gaps students are engaging with.

Our analysis has also helped us understand the difficulty in making weight visible as a focus for inquiry in the initial modeling. In early conversations, in both Ms. Lily's and other classrooms, there was often an absence of talk about the weight of water. Teachers had difficulty eliciting questions and puzzles related to weight from students' modeling, likely because the different representational systems (previous models, simulation, bottle breaking) didn't offer as many resources related to weight. Across iterations, contradictions and gaps related to volume have more consistently emerged in initial models and conversations than those related to weight and amount of water. We have found we need to rely on other strategies to introduce weight and to begin to make weight an aspect of the puzzle and a focus for modeling.

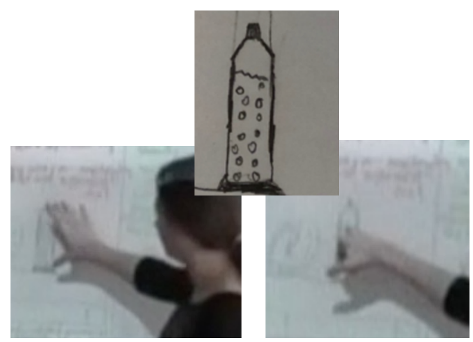
Mapping Constraints Across Conceptual and Empirical Models to Relate Molecules to Water Expansion

Another form of work that models can contribute as they interlock is when one representational system provides *constraints*—stable assumptions or must-haves—to focus activity or hold models accountable to (Nersessian, 2008). As Nersessian describes, constraint satisfaction limits the possible ways of proceeding in modeling, without specifying exact moves. In the episode above, some students, including Rafeal, took up constraints from the simulation (eg, molecules coming together as water cools), but these resources weren't yet stable enough to focus joint work. Constraints played a stronger role as students moved back from the vial system to examine their initial models in light of new evidence (Table 1).

In the following episode, the empirical model provided constraints such that students began to hold their molecular models accountable to showing expansion of water. It took place after students had completed the vials investigation and analyzed data representations, agreeing on the claim that "As water freezes, the water level increases, but the weight stays the same."

Several students began to note that they found this result puzzling, wondering how something could become bigger in volume but not weigh more. The team decided to ask them to examine three models (Rafael's, Sada's, and a teacher-created model that showed molecules multiplying (Table 3)), considering how each could explain water level increase and weight staying the same as the bottle froze. Students worked in small groups, then discussed as a class.

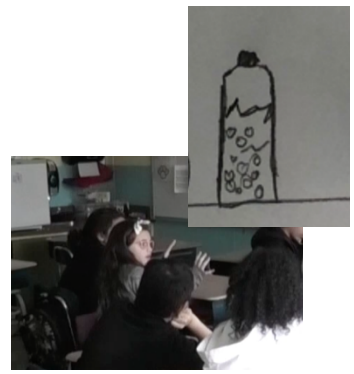
Episode Analysis. Ms. Lily first showed Rafael's model and asked whether it could explain how water increased in size as it froze. Rafael shook his head.

	Transcript	Parts of models referenced
1	Ms. Lily: Rafael why do you say no (.) it's great (.) this is your own model (.) it is okay that you think differently.	
2	Rafael: Because I drew it, the first one, bigger than the others	
3	Ms. Lily: So Rafael- That's okay, so you have new knowledge that you're using to apply to your thinking. It is great that you're changing what you're going to think about. So Rafael notices that his molecules are bigger than his last ones (.) can you say more about that Rafael (.) explain a little bit further.	
4	Rafael: Because the first one I did bigger- the glass bottle bigger and the other ones I forgot to like do the same height of the glass bottle.	
5	Ms. Lily: So you're noticing that the bottle is different (*hand outstretched*) (.) are you noticing anything that is different about the molecules inside (*points inside*)	
6	Rafael: Yeah	
7	Santiago: They are spread	
8	Ms. Lily: So talk to me because remember-talk to me about the molecules inside.	
9	Rafael: They're spreading (.) the molecules are spreading	
10	Ms. Lily: So when you go from the first one to the last one you're noticing that the molecules are spreading	
11	Rafael: No they're getting closer	
12	Ms. Lily: They're getting closer (.) Santiago were you raising your hand	

13	Santiago: Yes because I think (...) that you were telling what is happening with the molecules on the first bottle they are spread from the sides and the second picture they are getting closer (*gestures with hands*) and on the third picture the bottle explode and the molecules is all together (*squeezes hands together*).

The sequence begins with Rafael articulating that his model did not show water getting bigger. His first explanation was that he drew the bottle in the first frame larger than the next two. At the beginning of the work, the size of the bottle, and the ability to compare water levels within the bottles, was not of particular importance to Rafael, as he primarily worked with constraints related to water freezing and becoming hard. However, these aspects of the system were now important, and foci of revision.

In these initial reactions, ideas about bottle size (and, potentially, water level) and molecules were elicited but they were not connected in students' talk. That is, it still wasn't obvious to students as a group that a satisfying model would show molecules moving apart as water expanded. This was work that needed to be done together. Ms. Lily turned students' attention back to the question of whether the model showed how water can expand is it freezes, again drawing on the information from the vials system as a constraint, by asking whether a model that showed molecules coming together could explain how the water expanded, or got bigger, when it froze.

	Transcript	Parts of models referenced
1	Victoria: I don't know expanded but stay together.	
2	Ms. Lily: Ah so you don't know if it is getting bigger but you think they are staying together (.) so how does them staying together, how does that connect with getting bigger to you	
3	Victoria: I don't know (.) I don't know	
4	Casandra: They get away or they stay together like they separate or stay together.	
5	(*Excitement and overlapping talk, Victoria speaks in Portuguese, students begin to respond in English and Portuguese, Ms. Lily asks students to attend to Victoria and for Portuguese speakers to "help share her ideas."*)	
6	Victoria: Que muita pessoa falou que no segundo desenho elas estão separando e explodindo, só que como a gente pode ver no desenho lá eles se estão juntando. Então, a pergunta é como que eles explodiram e se juntaram (.) Então essa é a minha pergunta [Yeah because like a lot of people said in the second drawing that they are separating and exploding, but as we can see in the drawing there they are coming together. So how are they exploding and then come together (.) so I'm asking….]	
7	Francisco: I am going to try to explain what she says (.) she say (...) some peoples say the water is spread out and (inaudible) but this explanation the water is close together.	
8	Ms. Lily: Okay so some people are saying that the molecules are spread out but this picture is showing them together	
9	Victoria: Fala que essa é a minha pergunta porque não sei se eles explodiram ou se juntaram. [Say that that is my question because I don't know if they exploded or came together.]	

Victoria's statement in Line 6 suggests that she was taking up the model for sensemaking. First, she began, "a lot of people said," indicating an engagement with others' ideas about the model. She then used "but…" indicating that she was experiencing a tension or contradiction. This tension helped her establish a gap, which she indicated with a mechanistic question, "How are they…" She further expressed that she saw a contradiction (Line 9), putting "exploded" and "came together" in opposition. Over the next few lines, students helped translate Victoria's ideas and several more students participated, co-constructing a puzzle of the relationship between molecules coming together and molecules pushing out in a way that could account for water level increasing, with Victoria, Ms. Lily, and Casandra agreeing on the question, "How can the bottle explode if they come together?"

This conversation differed from the discussion of Rafael's model in Episode 1, in that water expansion was now considered a "must-have" or "must-explain." That is, constraints from the vials focused students' activity, strengthening the contradiction in Rafael's model by holding one part stable: the need for water to expand. However, students' (and Ms. Lily's) references moved fluidly across plural nouns (they, the molecules) and singular (the water, it). It was still challenging to both separate and relate the observable phenomenon of the volume of water expanding and the molecular entities that were needed to explain the perceptual phenomenon, and it was still difficult to decide whether the constraint of expansion applied to the observable space the water took up, the molecules themselves, or both.

Ms. Lily then brought conversation back to the constraints imposed by the vials investigation, returning to a previous slide that restated the claim from the investigation, reviewing it and re-representing the water level on the slide (Figure 1). She then asked whether and how Rafael's model was consistent with this finding, writing the claims beside the model in black marker, where they would stay as she showed different student pen-and-paper models.

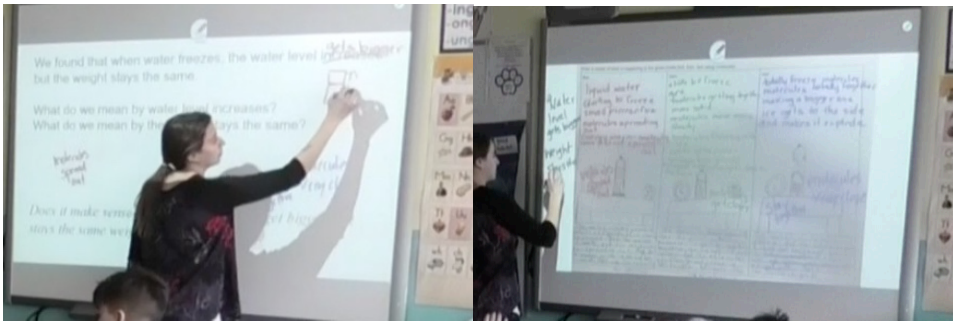


Figure 1. Ms. Lily re-introduces and represents the claim from the vials investigation

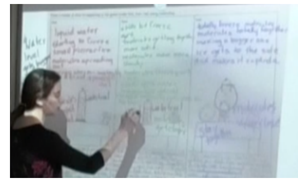
Bertrand then sought to understand how, and whether, Rafael had represented the level of the water in his picture. Rafael drew the edge of the water in the first and second frames, showing it as a jagged line in the second frame (perhaps to indicate ice), then used a jagged line where the bottle broke in his third frame. For Bertrand, the “line” across the top of the bottle in the third pane could stand in for either breaking or water level. In this exchange, Bertrand attempted to map the constraints of the vials (the model must show water level increase) to the initial model, stabilizing the relationship between the empirical model and models of the bottle breaking.

As several conversations began around the classroom about the meaning of the “line” in each frame, Rafael interjected,

	Transcript	Parts of models referenced
1	Rafael: Something first that I need to say is that like the water level of the second one and the third one needed to be bigger than the first one because I drew the bottle bigger and then put the water level in the first one higher.	
2	Ms. Lily: So that's...so it seems like that's you're thinking now, using the information that we learned that water level gets bigger, that your water level needs to get bigger as well.	
3	Rafael: Yeah.	
4	Ms. Lily: But the way you drew it when you didn't know this information, which how could you we didn't do the	

experiment yet, is the water level getting bigger or did it get smaller?

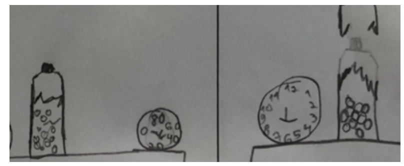
5 Rafael: Smaller.



6 Ms Lily: It decreased. Yeah, so your water level went down. It went down.

7 *(Rafael and Ms. Lily walk through the water level and bottle breaking representations in each frame).*

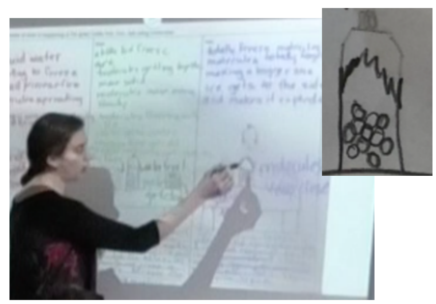
8 Ms. Lily: So your water level, it went down, and then what happened here? (*pointing to the third pane*)



9 Rafael: It freezed and exploded. The glass bottle exploded.

10 Ms. Lily: So, it froze and then does this water level (*pointing to the third pane*) show that it gets bigger or smaller?

11 Rafael: Bigger.



12 Ms. Lily: It shows that it gets bigger? Do the molecules that you drew match the water level you drew? (*gesturing to the third pane)*

13 Rafael: No.

14 Ms. Lily: No. So, your molecules show, did they expand with the water level, or did they not expand? Did they get bigger (gestures hands out) with the water level or get smaller (brings hands together) with the water level?

15 Rafael: Smaller.

16 Ms. Lily: Yeah, the molecules got smaller. They went down. Hmm.

17 Bertrand: That was my question that I was asking, is that water level or is it breaking.

Here, Ms. Lily oriented to the difficulty of coordinating the molecules and water level. She spent two minutes with Rafael working through how his drawing represented the water level, the bottle breaking, and molecules. In their talk, we see Ms. Lily and Rafael handing agency to the model and the features in the model. They did not talk about what *Rafael* meant to show or explain, nor did they critique his work. Instead, they talked about what the molecules and water level are doing pane to pane, and Rafael indicated the water level "needing to be bigger." To facilitate this kind of engagement with the model, Ms. Lily, at the beginning of the exchange, positioned the model as "the way you drew it when you didn't know this information"

(Line 4). Ms. Lily positioned the model as a tool to work with—one that could help students see gaps between the constraint of water expanding and the way that the molecules are positioned, establishing the need for a set of ideas about molecules that would allow students to coordinate what molecules do with observed properties of freezing.

Francisco next raised his hand and reintroduced ideas from the simulation, interlocking them with the current model, by remembering molecules coming together in the simulation, positing a mechanism by which molecules coming together could create an explosion that increased the water level, and linking that mechanism to what Rafael had depicted in the last pane of his drawing. Santiago began to work with this idea to consider further mechanisms, namely trapped air, that could support it. Students treated the contradiction established by the community, with the support of constraints from the vials, as a gap they could work within to develop explanations.

Ms. Lily then re-introduced Sada’s model (Figure 2), asking how that helped students think about their questions. María described the movement of molecules outward, showing that she took this to be important, potentially in light of the developing question about how molecules needed to show water pushing outward or rising. Santiago contributed, “The molecules on Rafael's drawing, the molecules are in the middle that is why I think the air is making the pressure, but when I look at Sada’s drawing, I change my mind because I think the air stays at the middle of the bottle and the molecules make the pressure at the glass.” Over the next several turns of talk, students mapped the molecular positioning in Sada’s model to the edges of water, with several students noting that they found this second model more satisfying.

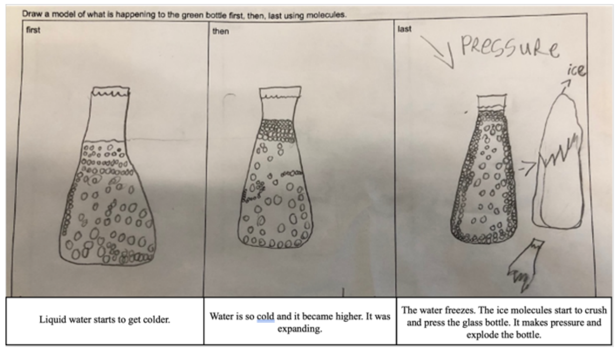


Figure 2. Sada's Model

In this episode, drawing on constraints provided by the vials system and data models supported students to return to their initial pencil-and-paper models and work with them in new ways. Students continued to explore the contradiction in Rafael's model, but with new resources to focus activity. There was more attention to how the water molecules could both come together as they froze but also get to the edges of the water to cause it to expand, with molecules used as an explanatory mechanism for water expanding. Students co-constructed this mechanistic puzzle, working with Rafael's model in light of new constraints and revising their thinking. The first step was recognizing representational choices that were not consistent with new constraints (the size of the bottle, the need to represent the edge of the water, whether the model showed water level rising). These, in turn, could be coordinated with puzzles about molecular positioning and arrangement. Here, constraints supported students to hold coherence across different conceptual and representational levels (Krist et al, 2019) and deepen the puzzle that was emerging for the class (how can water expand or take up more space but still weigh the same).

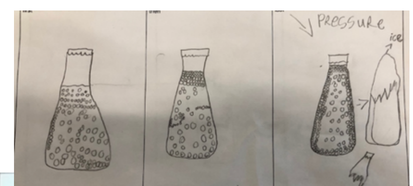
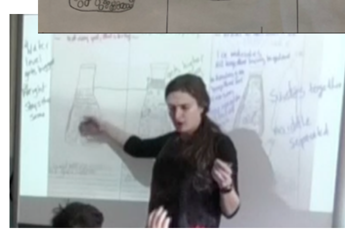
Constraints from empirical models across implementations. Across implementations, constraints have served an important role in classrooms' sensemaking and conceptual progress. In initial work, ideas like molecules coming together, water expanding, and weight vary across individuals and classrooms, with some individuals orienting to them as assumptions while others don't. Working with the vials constrains students' thinking about weight to a before-and-after comparison of a measured property, which focuses discussion. We can then make use of the finding that water expands but does not weigh more as it freezes to evaluate and revise models, and to develop puzzles about what molecules are doing that support further work. Further, *after* introducing the law of conservation of matter and connecting that to number of molecules, we have found that these new ideas come to function as key constraints for students' final models and for their further work with evaporation and flow of matter in ecosystems later in the year. Students articulate contradictions and gaps as they develop new models of these phenomena and pose questions about where molecules and matter go. Without constraints, it is difficult for these questions to emerge.

Across implementations, as seen here, we have found that using constraints to rethink earlier representational choices, develop coherence across representational levels, and compare models in light of new information is not always easy. This work can be supported by the teacher continuing to hold new findings as a constraint, working with the model at hand to see what it implies, helping students articulate questions and alternative explanations, and introducing new models that help students see alternative representational strategies (e.g., as Ms. Lily re-introduced Sada's model, where the molecules did map to the edge of the water).

Representational Surplus: Seeing New Representational Possibilities for Weight

A third form of work we have oriented to is representational surplus, which provides modelers new resources to work with. We draw from insights that all representations bring "surplus meaning," or implications that may or may not apply to target systems and phenomena (Hesse, 1966; Nersessian, 2008). Representational surplus occurred as students generated a form or choice to meet one need and other students took up that unintentional aspect of the representation as having implications. The ensuing discussion could lead to students to new questions and new representational possibilities, supporting conceptual progress. While we saw representational surplus operate throughout Ms. Lily's class's activity, it became particularly powerful as students moved from re-considering models in light of how they explained expansion to considering how Rafael's and Sada's models could account for the finding that the weight of water remains consistent across phase change.

Episode analysis. As Victoria was explaining that she considered Sada's model more useful than Rafael's for showing water expanding, she also noted that, "I don't know the weight of this water bottle… because it is a drawing." At this stage in modeling activity, it was not entirely clear to students how to see or evaluate weight in the pen-and-paper models.

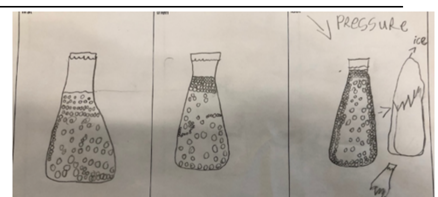
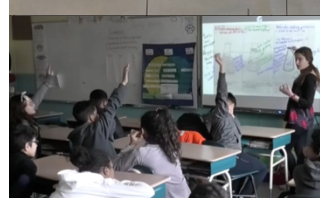
	Transcript	Parts of models referenced
1	Ms. Lily: So, does anyone have any thoughts about how can we figure out if the weight is the same from this drawing of the bottle to this drawing of the bottle? How would you know if the weight is the same? Francisco?	 
2	Francisco: Maybe the size?	
3	Ms. Lily: Maybe size. So maybe we can look at weight by size. Size of what?	
4	Francisco: Size of the bottle. The water.	
5	Ms. Lily: Size of the water. Size of water. Okay. Any other ideas? How can we look at weight when we look at these water bottles? Rodrigo?	
6	Rodrigo: I think it stays the same and is heavier. Because like the molecules are light… The molecules in the first one like stay like, Como se diz mais leve? [How do you say lighter?]	
7	Multiple students: Light	
8	Ms. Lily: What do you mean that the molecules are light. What does that mean? *(multiple students raise hands and speak up)*	
9	Ms. Lily: Do you want to try *(points at Rodrigo)*? What does it mean that your molecules are light?	
10	Rodrigo: Because the first one has not- Como se diz nao muy menos [How do you say much less?]	
11	Students: "not as much" "not as many"	

12 Rodrigo: Because the first one has not as much as the next one.

13 Ms. Lily: Okay so in this one *(points to Frame 1)* the molecules are light because it doesn't have too many (.) okay I am going to write that down (.) Rodrigo thinks the molecules are light because there aren't that many. What do you think about that?

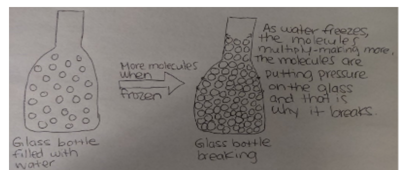
In this episode, conceptual progress occurred as Rodrigo connected the number of molecules to weight through comparing the number of molecules in each frame. Sada did not intend to show weight increase. However, her initial goal to show water expansion led to additional molecules at the top and sides of the bottle. When she was asked about this feature in the initial discussion, she briefly said it was accidental and discussion moved on. Here, Rodrigo engaged with this non-purposeful representational feature of the model (number of molecules) to consider weight change. Thus, representational surplus did work to provide the class with new resources for relating molecules and weight.

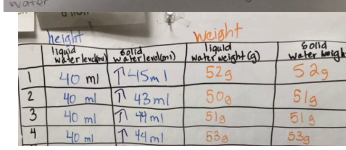
Students took up these resources to reason through Sada's model.

Transcript	Parts of models referenced
1 Rafael: One question I have is like how does the molecules (.) how does the last one have more molecules than the first one? *(audible agreement from other students; several hands raised)*	 
2 Ms. Lily: So that is a great question (.) Rafael can you say more about why you're coming at that question (.) why does this bottle (.) why does it have more molecules than this bottle (.) why is that a question for you?	
3 Rafael: Because like that's like crazy to think about how does the molecules (.) how does when it turns to ice get more molecules and where does the molecules come from?	

Here, Rafael questioned the very idea that the number of molecules could increase as water freezes, beginning to seek a mechanism through engaging with the model, then continuing to press on the idea that the number of molecules could increase, wondering where they could come from. This conversation was taken up by other students; first as several raised their hands right as he spoke, and then in the following discussion.

	Transcript	Parts of models referenced
1	Francisco: Maybe the molecules multiply (.)	
2	Rodrigo: I agree	
3	Francisco: and I think molecules don't have weight.	
4	Ms. Lily: So you think molecules don't have weight and you think that molecules can multiply?	
5	Francisco: Because maybe the other model	
6	Ms. Lily: The other drawing? The last one?	
7	Francisco: Yeah you see that (.) it is the same thing that we have here (.) and you see the data (*points to the data table on the wall).*	





	height		weight	
	liquid water level(ml)	solid water level(ml)	liquid water weight (g)	solid water weight
1	40 ml	↑45ml	52g	52g
2	40 ml	↑ 43ml	50g	51g
3	40 ml	↑ 44ml	51g	51g
4	40 ml	↑ 44ml	53g	53g

Here, we see Francisco proposing a new way to interlock the models, suggesting that molecules might not have weight, and reconnecting this idea to the data showing that weight does not increase as water freezes.

Across this conversation, the representational surplus from Sada's initial model began to do work for students as they considered what it might mean for water's weight to stay stable even as its volume expanded, drawing on constraints from the vials system. They worked with Sada's model as a tool for sensemaking, articulating how and why questions, speculating new explanations, and following through on implications (how can something come from nothing; maybe molecules have no weight). These questions and tentative explanations could support a return to the simulation guided by the questions, "Do water molecules become more water molecules as liquid water becomes solid water?" and "How can something get bigger (expand) but stay the same weight?" Similar to Rafael's water level discussion, we note students moving away from discussing what Sada meant to show and handing agency to model, thinking about what it meant that there were more molecules and what the implications might be.

In this episode, models did work in relation to each other to help students develop ideas and questions about weight. With the constraints and puzzles from the vials system in mind, students returned to their initial models, which were not initially drawn with a focus on weight. The representational surplus from one model (drawing extra molecules to show expansion) was recruited and, in turn, leveraged molecular explanations toward observable descriptions of weight and new questions. Thus, interlocking models—holding explanatory pen-and-paper models accountable to findings from the vial system— supported students to make conceptual process through seeing molecules as related to weight and generating a need for new resources, situating a return to the simulation to see what happens to molecules as water freezes.

Representational surplus across implementations. Across iterations, we have found that beginning to consider weight as relevant, interesting, and important is supported later in the sequence as students have more resources to bring together. This work requires them to see and leverage representational aspects that are not typically salient at the beginning of their modeling work. Ideas of weight as a perceptual quality and number of molecules as connected to weight or as constant in a closed system *sometimes* emerges for *some* students early in the work. However, these ideas can be leveraged and connected in new ways when interlocked with the constraint of stable weight and the developing puzzle of how something can get bigger but not weigh more. We have found that introducing the multiplying molecules model at this point in the sequence (either from students or the fictional model shown here) often supports students to note contradictions, pose new mechanistic questions, and consider counting molecules in the simulation to make progress in figuring out how water expands.

While representational surplus is powerful, it can also be difficult to work with. Inviting and amplifying this form of work requires thinking with models, essentially handing agency to the models, as we saw Ms. Lily and her students doing, rather than focusing on individuals' intent. In their first engagement with Sada's model, students did start to ask about why there were more molecules together around the edges and why there were different size molecules. In these cases, Sada said that this was a mistake or something she did not mean to do, and conversation shifted to the next question. Sada had left the class before her model was shown at the end of the sequence, which meant it wasn't possible to ask about her intent; this might have been another reason that conversation focused on the model, attributing agency to it. In one iteration (Fall, 2021), Ms. Shaw found the move to revisit initial models too difficult and leaned more heavily on other ways into the final modeling work; specifically, engaging students in making sense of the puzzle of how something can get bigger but not weigh more, and drawing on a student's analogy of a slinky to connect molecules to the "stuff" in the slinky (or water) and support students to explore the simulation. In a recent implementation, a teacher decided to have students engage with the fictional molecules multiplying model before returning their own, a move that made visible the potential implications of the number of molecules and allowed students to work with this and other ideas in their own models.

Summary

Across implementations of the design, the four forms of work we describe here–

contradictions, constraints, representational surplus, gaps—have emerged in the intersections of interlocking models and have supported students' sensemaking and conceptual progress. These forms of work benefit from designers' and teachers' support. Table 4 summarizes these findings.

Table 4.

Findings about Forms of Work and Ways to Support Them

Form of Work	Description	Can do work by helping students…	Ways to support this form of work
Contradictions	Resources drawn from across multiple representational systems are in tension.	Engage with others' ideas. Follow through on the implications of and evaluate models. Develop puzzles. Develop a sense of what might count as a satisfying explanation.	Select student models that involve tensions in elements. Direct students back to the model under discussion. Orient shared conversations to contradictions and gaps. Name different ideas and articulate where students are drawing them from.
Constraints	Aspects of one model serve as a must-have for another model.	Engage in focused conversations drawing on common ideas and definitions Coordinate micro-level and observable features by holding one scalar level constant.	Hold elements or agreements from other models as constraints by asking students whether and how their models show or explain [constraint]. Record constraints in a public place. Introduce new models that show alternative representational strategies and engage students in model comparison.
Representational Surplus	Representations bring with them meanings and implications the modeler might not fully interrogate until put in contact with another model.	See new elements of models as consequential and useful (e.g. number of molecules).	Introduce fictional models that accentuate aspects of models implicit in students' work. Shift from modelers' intent to model agency in conversation: "How could you have known that," "So does this model show," "Did your molecules expand with the water level or did they not expand?"
Gaps	Visible places where current understandings aren't yet sufficient to	Pose mechanistic questions of models (how does the ice get to the sides). Focus work with other models (simulations, canonical models).	Listen for students' sense of gaps in their discussion of contradictions and representational surplus. Help pose these as questions for the class to address. Sequence and frame modeling work so that complex and canonical

	connect resources in an explanation.	representational systems are introduced to address gaps students have identified.

Discussion

Research on supports for K-12 classroom modeling has made progress in describing principles (Gouvea & Passmore, 2017; Krist et al., 2019; Schwarz et al., 2009), teacher practices (Ke & Schwarz, 2021; Vo et al., 2019), and scaffolds (Windschitl et al., 2020) that can usefully guide modeling work. This paper explored how the representational forms and relations between models can be foci for design and teacher support of modeling activity. As we describe below, attending to models as co-participants and designing for models to do work by interlocking can continue to support curriculum designers and educators to develop powerful modeling experiences.

Models as Co-Participants in Sensemaking

This work is guided by a desire to create learning environments where students are supported in meaningful sense-making activity and make conceptual progress through sensemaking. Like a few previous studies (Manz, 2015; Pierson et al., 2020; Tobin et al., 2018), our analysis shows how students and models can work together in a dance of agency (Pickering, 1995) from which sensemaking purposes, practices, and ideas are emergent. In each episode, we detailed students taking up modeling for sensemaking by asking mechanistic questions, evaluating models' implications, engaging with others' ideas, articulating puzzles and problems, and revising their ideas and models. These purposes and practices were not performed entirely by the students, even with teacher support. Students did not begin episodes by stating contradictions or revisions; instead, resources within or across models, when brought into relation, provided something for a student, and then multiple participants, to begin to work with. We described how students and teachers handed agency back to the models as tools-to-think with. Across our design and re-design, we have been able to describe the different kinds of resources that different models could offer and when in activity they did so.

Taking a perspective that models can do work allows us to design sequences where teachers can act to support the work students and models are doing together. If we treat modeling skill as something that is held by the individual, we are more likely to get frustrated, decide students aren’t yet capable, or over-scaffold. In contrast, if we look at both modeling practice and conceptual progress as an interplay between students and models, we have more design tools at our disposal. We can examine models for what they might contribute, shift where in a sequence models come based on the resources students can bring to their work with them, engage with students to use models to construct puzzles and questions for further work, and consider our framing language as a support for purposeful sensemaking with models.

Designing for Models to Do Work in Relation to Each Other

Pierson and colleagues (2020) invite us to think about the conditions under which models can do work, arguing that computational models have affordances for youth to treat them as participants, namely their probabilistic nature and invitation for iteration. Here, we demonstrate that models that are often conceptualized as relatively static (pen and paper models; empirical models such as vials) participate in sensemaking when they are brought into relation with other representations. This finding is consistent with work on multiple representations (Ainsworth, 2008) and with the implicit design of units with modeling progressions (e.g., Ke et al., 2021; Kenyon et al., 2008; Vo et al., 2015). Descriptions of design and learning, however, have typically focused on sequences of models without showing the work that models do in relation to each other or highlighting the moments where models come together as particular kinds of opportunities for students to take up models as tools for problematizing, exploring new ideas, explanation, or revision.

The four forms of work described here—contradictions, constraints, representational surplus, and gaps—are named in descriptions of scientific practice (Hesse, 1966; Nersessian, 2008) and, to some extent, present in other studies in students work with multiple models. Gaps have been central to perspectives that emphasize problem-formation (e.g., Phillips et al, 2018) and sense-making (Odden & Russ, 2019), though few studies have investigated models' roles in presenting gaps for students to work with. Gouvea and Waugh (2018) describe the role of constraints in focusing undergraduates' work with coupled systems, while Blikstein and colleagues' (2016) discussion of discrepancies across models aligns with the ways contradictions supported students in our analysis. The role of representational surplus is, to our knowledge, a new focus for research and design. However, it connects to some research showing how representational qualities of systems can bring up new questions and make new possibilities evident, when brought into contact with models that don't have those qualities because they weren't considered relevant at that stage of activity (Wilkerson et al., 2015).

Designing for models to interlock, and understanding the specific forms of work that they can do when they interlock, can support designers and teachers in their efforts to help students engage in modeling. We have drawn on our findings to develop descriptions of potentially productive models for teachers to highlight at different points in activity (e.g., looking for models with contradictions between molecules coming together and water expanding early in activity; asking about models that appear to show molecules multiplying after students have established weight as a constraint). We have sought to describe what constraints are useful to focus modeling at what points in activity, and how to develop, or when necessary introduce, these constraints. Finally, we have recognized that it is sometimes necessary to shift conversations away from modelers' intent (i.e., what they aimed to use a model to show) and use moves that allow students to think-with-models (i.e., consider what a model implies about an idea or phenomenon).

Further, this work contributes to existing literature on using models to help elementary-age learners make conceptual progress in their understanding of the particulate nature of matter and the conservation of matter. It provides additional evidence for claims that students need systematic support to develop and stabilize and understanding of perceptual and measurable properties of materials (Smith et al, 2006; Jin et al, 2019) and relate these properties to micro-level processes. In this case, the range of models, and activity to interlock these models, provided support to articulate and stabilize a joint representation of volume and weight that could provide constraints and an explanatory target for students' work with molecules. We saw that how to apply these constraints was not obvious to students and described how teachers supported coherence across macro- and micro-features as students worked across representations. These findings suggest that further work can orient to systems of models that, in interlocking, support students to consider, stabilize, and make sense of concepts of matter as they engage in modeling matter.

Challenges and Further Work

The basis of our claims was comparative across episodes, in that we looked at moments in whole class discussion where models were and weren't doing work, seeking to develop process explanations that accounted for differences.This is consistent with methods of design research in early iterations of designs, which typically focus on whole group discussion and artifact analysis to trace the thread of joint practice and taken-as-shared understandings (Cobb et al., 2001). However, as Brown (1992) pointed out, this approach entails a danger, in that attention is drawn by the “golden moments” of classroom activity. Such methods may cause us to miss students who were not experiencing meaningful practice and underestimate the challenges of the work. Therefore, we acknowledge limitations and reflect on a few challenges that may not be visible in our analysis, along with our plans to address them.

First, we acknowledge the complexity of this work and the need to further consider how teachers can be supported to do it. Within the co-design team and in co-teaching, we have struggled with how to phrase modeling questions; how to move between modelers’ intent and models’ agency; how to unpack the specific elements of one model when students are already seeing them in light of another; how to be responsive to the work that students are taking up models to do; and when to remind students of particular constraints, contradictions, and gaps. In response, we are working to name the components of modeling conversations and develop descriptions of principles and supportive teacher moves.

A second ongoing challenge is how to create curriculum materials that are streamlined while, at the same time, providing opportunities for teachers and students to engage in co-constructing a modeling system and pursuing refinements in light of emerging questions. Like many researcher-developed instructional sequences, ours takes time and can feel to teachers and students that it stretches too long. In some cases, we have been able to use our developing understandings of interlocking models to make choices about what is *most* useful for students to grapple with, and what might be *less* useful. For example, over six implementations, we have found that students’ initial thinking about weight, volume, and their relations across phase change is so broad that it is most helpful to begin the empirical investigation by providing a set of materials (vials and scale) that focus students’ investigation design. Questions about measure and precision appear more meaningful to students *after* the investigation than in the design of it; so we design for these conversations to occur then, rather than engaging in long conversations to design the investigation. But in other cases, it is less predictable what will come up and where to expand. We have sought, but struggled to, offer choices for teachers in how to take up students' ideas and/or offer resources that support and bound activity without curtailing or dismissing students' thinking.

Finally, we acknowledge that we have not yet fully conducted the analytic work to understand *who does (and who does not)* experience their modeling activity as purposeful and productive. At its heart, this paper is motivated by a larger call to expand our thinking about science practice and representational practice toward forms and relations that do work for young people. Recent work has looked closely how modeling can allow students to see their interests and strengths reflected in modeling work or, alternatively, can reify hierarchies in whose ideas and ways of modeling matter (Chappell & Varelas, 2021; Pierson, 2021; Solomon et al., 2022; Suárez, 2020). We have some evidence that the modeling design served to invite and support multilingual students, including one (Victoria) who had just arrived in the class, and that the forms of work we described often lead to explosions in class participation as an idea or puzzle is made visible to the class. But our analysis did not fully examine who was not taking up models as co-participants and why. Nor did we examine emergent or expansive modeling forms that others have pointed to (e.g., Solomon et al., 2022). In our current work, we are developing methods for understanding how students perceive modeling activity, who is participating, what modeling forms are generated or expanded, and whether (or how) students take up ideas from class discussion in individual tasks or small group tasks that follow.

Conclusion

Our findings offer implications for the design of learning environments that engage young people in meaningful and productive modeling. First, this article demonstrates how carefully designed modeling work can elicit and build from young people's ideas about phenomena and recognize children's competent and creative engagement in model-based sensemaking. Second, researchers and educators can consider how to develop and connect sequences of modeling work and support students to recognize models as bearing on each other. Third, design-based researchers can continue to develop fine-grained descriptions of how and when interlocking models can support conceptual progress. More work remains to better understand how these approaches can be useful to curriculum designers, teachers, and young people.

Data Availability

Transcripts and student work with pseudonyms are available upon request.

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Endnotes

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[i] We used the Basic States of Matter (Phase Change) simulation from PhET™ Interactive Simulations, © University of Colorado Boulder, 2022-2023: https://phet.colorado.edu/sims/html/states-of-matter-basics/latest/states-of-matter-basics_en.html.

[ii] We use the term representational systems to denote systems with specific entities and representational affordances, e.g., simulations or vials with markings for volume. We consider these to function as models when they are taken up in service of figuring something out and communicating how it works. For example, the simulation is a representational system with settings for temperature and molecules that move in different ways. It is used as a model by students when they take it up to explain what molecules do when water freezes that allows water to expand without weighing more.

[iii] Consistent with design-based research, the design was slightly different in each of the three iterations we have developed and analyzed—based on learning from the previous iteration and design changes made day-to-day in light of students' activity. The representational systems students engage with have remained constant, but the order and movement between them has shifted. The design that we describe here is the second iteration, as that is the data that we focus mostly closely on in the paper. Table 1 in the supplemental materials shows changes made across the iterations.

[iv] In three of four iterations examined here, our work was substantially disrupted by the Covid-19 pandemic: In March, 2020, as it was cut short 4/5 to completions, in Ms. Shaw's implementation in Fall, 2021 as she faced welcoming her students to school after a full year of remote instruction in a classroom with masks and ventilation that made it difficult to hear each other, and in Ms. Lily's class (Winter, 2021) at the height of the Omicron wave.

[v] Throughout the transcripts, we provide close images of the parts of models referenced, as well as gestures indicating what part of the model participants are referencing, to help readers follow how participants are working with models. When students are comparing multiple panes, we include images of the full drawing, while when they reference one part, we include just that pane.