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Interlocking Models as Sites of Modeling Practice and Conceptual Innovation

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Abstract: A central goal of both professional and classroom-based scientific communities is building and testing explanatory models of the natural world. The process of modeling a complex phenomenon often requires working across representational systems of differing scales, modalities, and purposes. When put into contact, entities across multiple representational systems can become related or "interlock." This paper describes how students drew from multiple representational systems to construct "interlocking models" and how reasoning with interlocking models supported meaningful practice and conceptual innovation. We present the design and findings from the implementation of a fifth-grade investigation into the conservation of matter. We describe the process of how contradictions between representational systems surfaced and led to interlocking models. Our findings suggest that students can recognize and take up interlocking models that provide a purpose for students to critique and refine their understanding.

Introduction

While model-based reasoning and explanation is a driver of science practice and increasingly of science education, how to design and support learning environments where young students take up modeling as a meaningful practice—one that is purposeful, agentive, and conceptually productive—is an enduring question (Berland et al., 2016; Manz, 2012). In this paper, we explore what can be learned about classroom modeling from a key practice of laboratory science—interlocking models. We share findings related to the challenges and opportunities of designing for interlocking models in a fifth-grade investigation of the conservation of matter. We conclude with insights into how students productively recognized and took up the tensions and pushbacks surfaced by contradictions and interlocking models.

Opportunities and Challenges in Classroom Modeling

Consistent with philosophers and sociologists of science, we conceptualize science as a modeling enterprise (Giere, 1990; Windschitl et al., 2008). Science involves constructing, evaluating, aligning, and refining models in light of their joint bearing on a question or purpose. Models take on many representational forms, including equations, theories, diagrams, and simulations. In classrooms, orienting activity around developing, testing, and revising models can support students to develop science understandings as they engage meaningfully in scientific practice (Gouvea & Passmore, 2017). Yet, how to design and implement learning environments where students make progress on important science ideas as they develop and revise models is not yet fully understood. Teachers can take up models as places to hold ideas or orient so fully to developing canonical models that students have little agency in constructing or critiquing models (Lehrer & Schauble, 2006). Students, who are new to the modeling game and conduct it in communities of practice that differ substantially from those of scientists, may not necessarily take up models as tools for reasoning and communicating (Schwarz et al., 2009). Researchers are still debating how exactly to prioritize students' authorship of science practice as compared to the development of canonical understandings that were developed over periods of time and with tools impossible to instantiate in the classroom (Osborne et al., 2018). To orient our work on these challenges, we draw from situative and socio-cultural accounts of learning that treat practices and ideas as resources participants draw on, re-organize, and over time stabilize as they engage in meaningful activity in communities (Hall & Greeno, 2008). From this perspective, the purposes that students take up for modeling (to demonstrate understanding, to compare ideas, to recognize and orient to contradictions across ideas and evidence) are both of central importance in supporting meaningful science practice and are themselves emergent from activity. Key questions, then, are how (1) those purposes can emerge in activity and (2) how modeling can be productive, from students' point for view, for their conceptual work. Next, we consider how the use of interlocking models can help the field make progress on these questions.

Interlocking Models in Science Laboratories and Classrooms

Rather than working with models in isolation, scientists align and integrate multiple models as they work toward building a more complete explanation of a phenomenon (Nersessian, 2010; Rouse, 2015). Nersessian describes how through this process models can "interlock" or come to be taken as bearing on one another. Once interlocked, one model becomes a potential site for new questions, challenges, or refinement of another. For example, neural engineering laboratories construct models consisting of the recreation of phenomenon *in vivo* (e.g., neural networks) as *in vitro* physical models (e.g., dish of neurons) and computational re-descriptions of models (e.g., simulation patterns for the dish). Accounts of interlocking models in science practice offer several potentially useful implications for supporting students to engage in agentive, purposeful, and conceptually productive modeling. First, individual moments of modeling are open-ended and tentative—with no promise that they constitute "progress." Second, interlocking models form a fabric that is not seamless, as information from different representational systems can be inconsistent or contradictory. Contradictions between representational systems can point toward conceptual gaps, discrepancies, and tensions. That is, a key source of conceptual innovation in science is the moments where models "speak" to each other and the differences in what they "say;" these differences can provoke problem-solving processes that drive the refinement of questions, methods, and tentative explanations.

In K-16 science education, designs for model-based learning such as the *bifocal modeling framework* (Blikstein, Fuhrmann, & Salehi, 2016) and *coupled methodological systems* (Gouvea & Wagh, 2018) have used multiple representational systems. These designs have primarily focused on how simulations and physical experimentation can support each other, showing that one representational system can become a source of questions for another and that differences in results can support students' further inquiry. In this paper, we sought to build from this work by pursuing a closer analysis of (1) when and how students come to see representational systems as bearing on each other and (2) how interlocking models can support moments of conceptual innovation, thus allowing us to better understand how educators might design for and support interlocking models in classrooms. To situate our analysis, we first describe the design of a fifth-grade science investigation into the law of conservation of matter in which students worked with multiple representational systems. We then describe how contradictions among emerged as a key mechanism that allowed students to begin to make connections across representational systems, treating them as models that could interlock, or bear on each other. We show how, through questioning and making sense of the contradictions, students developed interlocking models that served as tools for further reasoning.

Research Context & Design

The work reported here takes place within a larger design-based research study involving a multi-year co-design partnership (Penuel, Roschelle, and Schechtman, 2007) with a public school district in the northeast US. The goal of the project is to redesign the elementary school science investigation to better capitalize on forms of uncertainty that are usually removed from children's experience with empirical activity. In this paper, we report on the second implementation of an investigation co-designed with two teachers. The investigation addresses fifth-grade NGSS standards related to matter and its interactions, specifically that students "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" and "use a particle model to explain common phenomena involving gases and phase changes" (NGSS Lead States, 2013). Like other standards that we have unpacked with teacher co-design teams, these pose challenges for engaging children in meaningful and agentive modeling practice in which they make progress toward the canonical ideas held in the standards. First, why would students ask about and focus on the weight of substances as a measure of amount, rather than more perceptually available attributes, such as volume? Second, how could we support students to experience weight as not changing, when small fluctuations could be interpreted as confirming prior ideas? Third, how could we set this work in a context where students were making sense of a phenomenon they could experience and wonder about, when water—the only substance to exist in all three phases within earth's temperature ranges – behaves differently (expands as it freezes) and must be explained by a molecular, rather than particle, model? Fourth, how could students come to see the molecular models that they had been developing as useful for understanding changes (or lack thereof) in the size and weight across phase changes? Like many classroom investigations, the questions, measures, evidence, and conceptual entities that children are expected to use are only "obvious" in light of entire set of models that scientists have stabilized in relation to each other.

This context therefore provided a fruitful opportunity to explore using interlocking models. We developed a sequence of activities (Figure 1) in which students engaged with different representational systems: (1) watching a **video** of a glass bottle filled with water and placed outside in cold weather eventually exploding, (2) building **pencil and paper models** to explain why the bottle broke using molecules (drawing on previous work in which they had used a simulation and models to explore why dye diffuses at different rates in different water temperatures), (3) testing questions related to whether water was "getting bigger" using an **empirical investigation**, (4) creating a **data representation** to see what most of the vials did, and (5) returned to their **initial**

models and a **simulation** to develop a class model of water molecules spreading out when frozen—explaining the fact that the same amount, or weight of water, can take up more space when frozen and break a glass bottle. This process set up an introduction to the law of conservation of matter as a sensemaking resource with explanatory power, rather than as either an answer that students could arrive at through developing conceptual models or the "correct explanation" they could be told. Table 1 shows how we considered each of these to be distinct representational systems with specific resources and the potential to interlock.

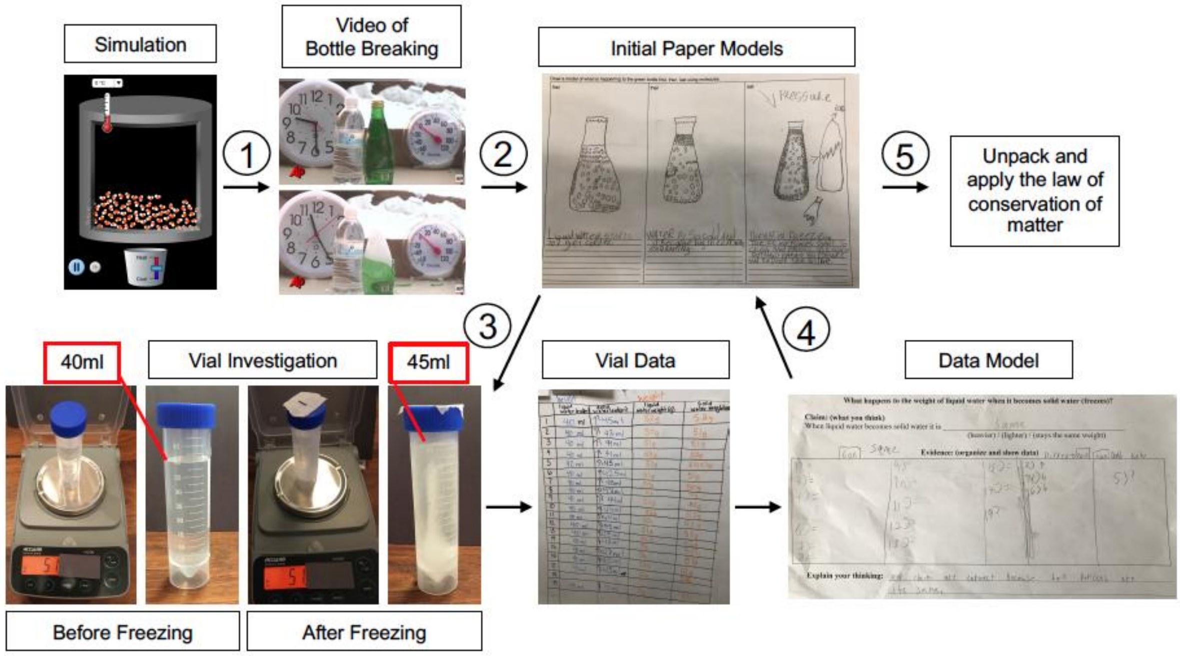


Figure 1: Sequence of Activities

Table 1: Overview of representational systems

Representational System	Conceptual and Representational Features	Opportunities for interlocking models
Simulation	Micro-level molecular representation of phase change in water; highlights how molecules move and arrange with temperature; keeps the number of molecules static; temperature an adjustable parameter.	Introduced in the context of water molecule behaviors under increasing temperatures; exploring the parameters and boundaries of the simulation led to questions about temperature decrease; offered students a canonical model of molecular behavior to apply to the bottle breaking; later, a return to the simulation used refute or support theories of water expansion.
Video of the bottle breaking	Macro-level perceptual representation of phase change; offered access to familiar sensemaking resources (e.g., pressure, air, materiality); static parameters but replayable.	Provided resources to support initial models of the bottle breaking and a context to reason with water getting "bigger" or taking up more space as it freezes.
Pencil and paper models	Student generated micro- and macro-level representation of how and why the bottle breaks using molecules; flexible and open-ended space for students to propose tentative explanations.	Context for students to bring together resources from the multiple representational systems to explain and refine explanations of the bottle breaking at different points in the inquiry.

Empirical model: Vials filled with water and frozen	Empirical; draws attention to measures of weight and volume (water level) and supports comparison across phase change	Observable and measurable evidence for water level; evidence that weight does not change, which can connect to number of molecules
Data model: Organized data set	Students organize and compare data to make visible what "most of the vials did."	Supports using data to develop a claim about what most vials did and what water does generally.

Analysis & Findings

Across the investigation, we found that students incorporated resources from multiple representational systems to build and revise explanations of water expansion and the conservation of matter. Further, we identified and described moments when systems *interlocked for students,* in that they came to see these representational systems as bearing on each other; for example by using micro-level information from the simulation to explain the macro-level phenomenon of the bottle breaking. In particular, one mechanism that appeared to support students' use of representations as models and their explicit recognition of these systems as bearing on each other was that of *contradictions.* We found that contradictions surfaced when students recognized gaps in conceptual or representational coherence as resources from different representational systems were combined or put side-by-side. When contradictions were made visible and accessible, they became sites of conceptual innovation as new ideas, questions, and even new contradictions emerged. While not all contradictions co-occur with interlocking models, or were contradictions the only evidence of interlocking models, we found that conceptual progress and meaningful practice could often be mapped to key contradictions. In Table 2, we unpack three contradictions that appeared key to modeling and conceptual progress. How each contradiction emerged and pushed back depended on how student perceived the purpose of the interlocking models. We use one contradiction—how solid water can expand if molecules come together as temperature decreases—to illustrate the emergence and work of contradictions and interlocking models.

Table 2: Overview of the role of contradictions across the investigation

Contradiction	How the contradiction emerged	Opportunities for conceptual innovation
1. How can solid water expand outward as it freezes if molecules slow down and come together as temperature decreases?	In the simulation, students saw water molecules slow down and come together as liquid water decreases in temperature. After watching the bottle breaking video, students thought that water expands as it freezes. Students drew on resources from both representational systems as they constructed their initial models.	Students recognized the contradiction between molecules coming together and water expanding, which highlighted a gap between their current understanding of molecules from the simulation and their perceptual understanding of the bottle breaking. Making sense of the gap led to discussions around different dimensions of size and an investigation to measure weight and water level before and after freezing.
2. How can something take up more space (increase in water level or volume) but still have the same weight?	Students conduct the vials investigation and come to the conclusion that as liquid water freezes, water level increases but weight remains the same. This empirical result conflicted with their perceptual experiences that as something "gets bigger" or takes up more space it also weighs more.	The results of the vial investigation—the weight remains the same but the water level increase in most vials—presented a puzzle. Settling the debate over the results required refining a molecular mechanism for water expansion that accounts for size (molecular arrangement) and weight (number of molecules).
3. How can molecules spread out (to generate pressure on the	In order to explain the bottle breaking, water must be	Students located micro-macro level gap between the molecular

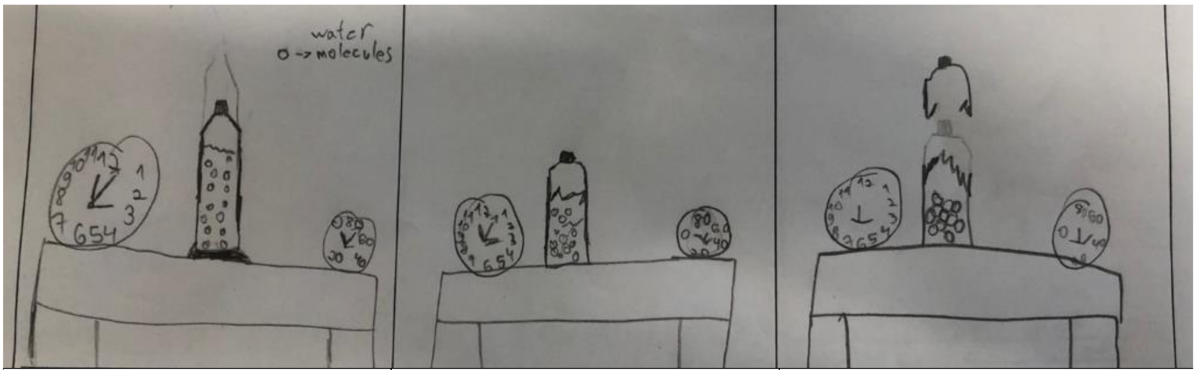
bottle) but stay together (produce a solid)?	expanding to put pressure on the bottle. This required a molecular model of water molecules spreading out as liquid water freezes. This model conflicted with their sensible ideas about solids with molecules tightly packed together.	model of water molecules spreading out but remaining as a solid prompted a need to return to the simulation to look closely to what happens to molecules at water's freezing point.

Focal Contradiction: How can solid water expand outward as it freezes if molecules slow down and come together as temperature decreases?

One key contradiction that came up over the course of the investigation was between molecular understandings of water and perceptual qualities of water expansion (increases in size, space, or amount). Students who drew on the simulation and earlier class models for how molecules behave as water freezes ran up against a tension in that their molecular understanding—molecules slow down and come together as temperature decreases—aligned with a commonsense understanding of solids (tightly packed, hard, immobile) but could not explain how water expands or creates pressure on the bottle. In the following sections, we illustrate this contradiction as students worked through pencil and paper models before the vial investigation (Figure 1; Points 2 and 3) and as they returned to their initial models to make sense of the results of the vial investigation (Figure 1; Points 4 and 5). We show that this contradiction provided a reoccurring tension at key junctures of the investigation but worked differently based on how and for what purposes models interlocked.

Emergence of the initial contradiction in pencil and paper models

We first consider Roger's (all names pseudonyms) pen and pencil model, developed at the start of the investigation. Students watched the video of the glass bottle breaking, discussed their initial theories, and were asked to draw a model that "showed what happened to the bottle using molecules." Roger's model (Figure 2) indicated a gap between previous models and the bottle breaking that he addressed by including ideas drawn from entities in the video context.



The water is not freezing yet. It is liquid. It is starting to freeze. But the water is warm, and the molecules are spreeding [sic] out. Maybe the energy or the molecules is warm. That is why the molecules are spreeding [sic] out.	The water is more freezed [sic], than the first time. The molecules is getting together, because the water is more colder. And the molecules is slowly and freezing. That happen because the temperature is colder.	The water is totally frozen. And the bottle explode. I think that happened because the lid freezed and there was not space for the cold air to get out. That's why the bottle explode.

<u>Figure 2.</u> Roger's model (handwriting replaced with typeface for legibility).

To develop his model, Roger drew on resources from the video of the bottle breaking, the simulation, and earlier class models. In Frames 1 and 2, we see Roger drawing on ideas from earlier work with the simulation and class models: that molecules come together as water gets colder. His writing is consistent with his drawing, linking water freezing to molecular re-arrangement and a decrease in speed ("getting together" and "slowly"). In Frame 3, Roger continued to show molecules coming together in his drawing, but his written description drew on ideas about cold air and the bottle's lid, from the video.

We see evidence of the simulation and the bottle breaking video interlocking in the Roger's model. In the first two frames, Roger's writing and drawing matched; he drew molecules coming together as the water temperature begins to decrease. In the third frame, he drew molecules packed tightly together as a solid, but then wrote about the bottle breaking because of the lid freezing and "no space" for the air (implicit relation to pressure). The mismatch between his writing and drawing suggest Roger might have understood that molecules coming together cannot fully explain the bottle breaking. Although he was quite sure that this is how molecules behave based on the simulation, in order to complete his model of the bottle breaking he drew on perceptual features of the video—the lid freezing shut, cold air inside the bottle, and lack of space. In short, the contradiction revealed a gap between what he was importing from the simulation and a mechanism for the bottle breaking. Thus, while Roger used molecules as directed and described by the simulation, they were alone not enough to explanation of the bottle breaking.

We see this moment of modeling as a site for conceptual innovation in two ways. For Roger, the search for new resources at the moment of needing an explanation suggested that he might not be satisfied with how his current understandings of molecules can help him construct an explanation. Second, from our point of view as designers and teachers, was that Roger was drawing on molecular arrangements, a resource of the simulation that would be key as we moved into the vial investigation and beyond but was able to sidestep the contradiction we hoped would surface by recruiting an alternative explanation – the air in the bottle needing to get out because the lid exploded. Further, we noted that his molecular arrangement did not correspond with the space that the water took up. Therefore, we chose Roger's model to show the class, wondering if other students would recognize gaps that could lead to further work.

The teacher next projected Roger's model, asked him to explain it, and invited other students to ask clarifying questions and offer critiques. Roger's initially individual model now became a context to collectively reason around the affordances and constraints of one model; with other models (those the students had drawn from themselves) put in contact with this model. While Roger did not yet find his contradiction problematic, other students noticed and probed the contradiction. Casandra asked, "How do the ice gets to the sides [in] the last one?" She noticed the contradiction of molecules coming together and the need of solid water to expand to the sides of the bottle. In addition, her question highlighted the representational need for molecules to represent the edges of water, either as liquid or solid. Her question, and those of other students, implied a need of and mechanism for water expansion not evident in Roger's model. Through her question, Casandra demonstrated how contradictions can elicit questions that surface the need for further explanation. Roger made use of resources from both systems that in turn led to a gap (the arrangement of molecules vs the ice filling the bottle; molecules coming together vs something exploding), community activity around his ideas supported attention to the space that water took up and the fact that the community did not yet have a sufficient model to account for this. This gap subsequently supported a need for the vial investigation (Figure 1; Point 3), in which there was a *reason* to remodel the glass bottle as a simpler system of freezing water measured in height (and weight, which was supported by other model contradictions; Table 1; #2).

Interlocking the contradiction with the vials investigation

After discussing their initial pencil and paper models and turning their attention to the amount or edges of the water, the class tentatively agreed that water "gets bigger" as it freezes and experienced uncertainty about what happened to the weight of the water. We then suggested that they test their ideas, introducing vials that they could fill with water, weigh, and freeze. We further supported them to organize and make claims about the class set of data, developing a consensus claim that "as water freezes, the water level increases but the weight remains the same." At this point, the class had strong empirical evidence that water expands in space but does not increase in weight, but were left with a new puzzle: does it make sense that something could get bigger (water level) but stay the same weight? We revisited three initial models in context with the multiple models we had explore thus far (initial models, the bottle breaking, and vials and consensus claim about water level and weight). We used Roger's model, conjecturing that returning to this model would support conceptual progress, as the representation of molecules coming closer together now contradicted both the bottle breaking video (water expands) and the results of the vial investigation (water level increases). After students considered all three models in small groups, we introduced Roger's model to the whole class with the question: Can this model explain how water expands (gets bigger) when it freezes? In their discussion, students continued to work through the contradiction embedded in Roger's model of the bottle breaking and drew on resources from the vial investigation. During the conversation, one student, Victoria, wondered of Roger's model,

1. Victoria: A lot of people said that they are separating and [expanding], but like we can see in the drawing there they are coming together. So how are they [expanding] and then come together (.) so I am asking=
2. Jackson: =Some people say the water is spread out and (inaudible) but this illustration the water is close together
3. Victoria: That is my question because I don't know if they expanded or came together

While Victoria is not yet directly attending to water level, her question resurfaces the contradiction embedded in Roger's model as a source of tension. As it is taken up by other students, Victoria positioned the contradiction as necessary to resolve before moving forward. The driving question of "Does the model explain how water expands (gets bigger) when it freezes?" was shifted by Victoria, and the students worked to unpack the now further complicated contradiction: How can water molecules come together but water expand? To illustrate, Jackson later responded to Victoria's question, returning to the contradiction and introducing a new mechanism for pressure,

> "the simulation, it was so cold that water molecules and [brings his hands together] and I think it is like this (.) these don't spread out but when the water molecules stay together they make pressure (inaudible) and air molecules don't have the space and the water level up and explode."

We view this moment as a powerful example of interlocking models and the role of contradictions. For Jackson, it is necessary that 1) molecules come together as temperature decreases, as evidenced by the simulation, 2) there must be a mechanism for pressure, as evidenced by the bottle breaking and 3) the water level increases, as evidenced by the vials investigation. All three of these resources are stable enough for Jackson that he introduces them as constraints for an satisfying explanation. In order for these to work together in a plausible explanation, Jackson introduced the idea that pressure on the molecules can explain expansion if you consider air. We consider Jackson's tentative explanation, still in reference to the initial contradiction, evidence that students were moving between the resources of the video, simulation, and the vials. In response, the teacher was able to pivot between representational systems, calling attention to specific aspects or entities to support interlocking models,

1. Teacher: Yes or no (.) does the water level get bigger in this picture (.) so I am going to call on a couple friends to explain their thinking (.) Barry (.) what are you thinking
2. Barry: So that isn't the water level [pointing to the third frame]
3. Teacher: So here yeah the water level what do you see different about the water level in this one
4. Barry: But Roger explained that that was breaking
5. Roger: Something 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 drew the bottle bigger and the put the water level in the first one higher
6. Teacher: So that's (.) so it seems like that's your thinking now using the information that water level gets bigger that your water level needs to get bigger as well

Through refocusing on a main resource from vials (Line 1), Barry was able to draw on water level and question Roger's model. Barry points out that Roger's "break" was where water level should be located in order to represent water expansion as a mechanism for the bottle breaking. Although Roger's model never intended to show water level increase, he was now held accountable to it in his drawing. Yet, Roger was able to revise his model in the moment, retrofitting water level to his initial drawing as a representational, rather than conceptual, mistake (Line 5). In this episode, the teacher called attention back toward water level, a resource not original to Roger's model, that keyed Barry to press on the contradiction such that Roger could articulate his conceptual understanding and cleverly re-represent the explanation provided by his initial pencil and paper model.

Conclusion and Implications

For authentic and epistemically honest modeling to occur in classrooms, designs for practice-based science learning must support students to see models as purposeful contexts for reasoning. This design approach is often discussed in terms of positioning models as tentative or open-ended, in service of scientific practice rather than reaching the canonical answer. Here, we contribute to this literature by explicitly designing in a context where (1) individual representational systems could not fully explain the phenomenon in question and (2) it is the interlocking, or coming together of partial models, that allows students to see models as tentative and incomplete *and* provides a source of conceptual innovation. For example, in our design the representational systems provided resources with different scales and modalities (e.g., the simulation versus the bottle breaking video). Only when these systems interlocked did students find a reason to interrogate the affordances and constraints within and across each representational system in order to develop an explanation of water expansion that made the law of conservation of matter useful.

In our analysis, we sought to understand how models came to interlock for students. We highlighted one mechanism, that of contradictions, that supported students to relate different forms of conceptual and representational information through the development and use of interlocking models. Following Roger's model across the introduction of new representational systems, we showed how contradictions emerged and came to hold interlocking models together. In Roger's initial pencil and paper model, he drew on resources from the simulation and video of the bottle breaking. However, these resources did not come to bear on each other until the contradiction (molecules coming together as water cooled vs moving apart to make the water push on the bottle) surfaced during whole class discussion. With the contradiction now a focus of activity, students questioned the relationships between representations and highlighted gaps in their collective understanding of the phenomenon. We found when these contradictions provided students with pushback, interlocking models emerged *for students* and did work to support conceptual innovation and meaningful practice. In our example, students were able to re-interrogate the contradiction of Roger's model with new assumptions based on the results of the vial investigation. As the contradiction resurfaced for students, it came with new puzzles and problems thus driving a need for iteration and further modeling. This analysis highlights how interlocking models might serve as a productive design tool to support students' meaningful modeling (Berland et al, 2016). It reveals key mechanisms that foreground relationships between representational systems (in this case contradictions). Supporting models to interlock from the students' perspective appears to provide the sort of flexibility and purpose we hope to see in emergent modeling practices as well as in a classroom modeling enterprise.

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