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Epistemic Gameplay and Discovery in Computational Model-Based Inquiry Activities

Abstract. In computational modeling activities, learners are expected to discover the inner workings of scientific and mathematical systems: First elaborating their understandings of a given system through constructing a computer model, then "debugging" that knowledge by testing and refining the model. While such activities have been shown to support deep science learning, difficulties building and using computational models are common and reduce learning benefits. Drawing from Collins and Ferguson (1993), we conjecture that a major cause for such difficulties is a misalignment between the *epistemic games* (modeling strategies) learners play, and the *epistemic forms* (model types) a given modeling activity is designed to support. To investigate, we analyzed data from a study in which ten groups of U. S. fifth graders (n = 28) worked to create agent-based computational models to discover the particulate nature of matter. Content analyses revealed that (1) groups that made progress—that is, that developed increasingly mechanistic, explanatory models—focused on elements, movement, and interactions when developing their models, a strategy well-aligned with the modeling environment; (2) groups that did not make progress focused on sequences of phases, a strategy not well-aligned with the environment; and (3) struggling groups progressed when they received guidance about modeling strategies, but not when they received guidance about model content. We present summary analyses and three vignettes to illustrate these findings, and share implications for research and curricular design.

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Epistemic Gameplay and Discovery in Computational Model-Based Inquiry Activities

Computational modeling activities are a popular, contemporary example of discovery-based pedagogy. Grounded in theories of Constructionism (Papert, 1980), the assumption is that learners will discover the underlying workings of target scientific and mathematical systems through two complementary processes. First, they are expected to discover their own tacit understandings of the system, by externalizing and elaborating what they already know. Since computational modeling tools require organization and precise specification, building models requires the learner to structure and interrogate their own knowledge and experiences, and consider exactly how such knowledge is relevant to the target system and conventional representations. Second, they are expected to discover the mechanisms that underlie the target system, by observing the degree to which the entailments of the executable models they and their peers have constructed reproduce that phenomenon (or fail to do so in ways that inform revision; diSessa, 2001; Penner, 2001; Van Joolingen, de Jong, & Dimitrakopoulou, 2007).

There is growing consensus that such activities have potential to support science learning (Clark, et al, 2009; Louca & Zacharia, 2012; VanLehn, 2013). However, students often experience difficulties that threaten this potential (Hmelo-Silver & Azevedo, 2006; Xiang & Passmore, 2015), including struggles to translate their understandings into models and to draw inferences from their models once constructed (Basu et al., 2016). Given that the processes of building and using models are the very ones expected to support discovery of scientific principles, it is especially important for researchers and designers to better understand these general difficulties.

To address this need, we reconsider Constructionist assumptions about computational modeling in light of Collins and Ferguson's (1993) notion of *epistemic forms and games*.

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Constructionism posits that computational modeling, like a language, can be made accessible to learners; once learnt, it allows them to express and reflect upon their knowledge in powerful new ways (Papert, 1980; diSessa, 2000; Wilensky & Papert, 2012). But just as there are different languages, there are different types of models. These model types, or *epistemic forms*, emphasize different aspects of target systems. Moreover, each epistemic form can be constructed through different modeling strategies, or *epistemic games* (White, Collins, & Frederiksen, 2011). It follows that simply building models is not sufficient for supporting science learning during computational modeling activities. It is also necessary that the epistemic forms supported by a given modeling environment are well-aligned with the intended goals of the activity, and that learners take up the intended epistemic games when building their models.

We explore the relationship between epistemic games, epistemic forms, and science learning in the context of a classroom study where ten groups of fifth grade students (n = 28; ages 9-11) used an integrated stop-motion animation and simulation environment to build models of evaporation and condensation. The activities were designed to support mechanistic reasoning by leveraging stop-motion animation to engage students in an epistemic game focused on describing molecular systems in terms of discrete objects in motion. Content analyses suggest that 8 out of the 10 groups created increasingly mechanistic, explanatory models over the course of the activity. Those groups that did not progress played a different epistemic game using animation than was intended, by creating sequences of scenes as if for a movie rather than focusing on discrete objects in motion. While both epistemic games–which we call “entities, movement, and interactions” (EM&I) and “scenes”, respectively–are well-aligned with stop-motion animation as an epistemic form, only the latter is well-aligned with agent-based simulation as an epistemic form, and with our learning goals for the activity. We illustrate these patterns in detail through three case studies: one of a successful group, one of an unsuccessful group, and one of a group that first struggled but then progressed with facilitation.

Background

The term *computational modeling* is used to refer to a cluster of related activities in the educational research literature. VanLehn and colleagues (2013) distinguished four such types of activities, all of which have been shown to contribute to science learning: *Model exploration; notational model construction*; *analytic model construction,* and *model-based inquiry*. This paper is concerned with model-based inquiry, which engages learners in constructing models of a target system for which few details are explicitly provided to the student. In these cases, students are expected to conduct research and/or leverage their intuitive understandings of a target system in order to decide what should be included in a model, and what should be the model's final form.

Over the past several decades, researchers have worked to make computational modeling accessible to young learners. One method has been to align the structure of modeling languages with what designers expect to be the structure of students' knowledge or experiences. Papert described the LOGO Turtle and its movement-based primitives—such as forward, right, and pen-down—as "body-syntonic…firmly related to children's sense and knowledge about their own bodies." (p. 63). Other environments use personalized pictures (Jackson et al., 1996), sketches (Bollen & van Joolingen, 2013), or natural language patterns (Wilkerson-Jerde, Wagh, & Wilensky, 2015). Löhner and colleagues (2003) summarized three common concerns in the design of modeling tools for science education: the closeness of representations to students' knowledge and experience; whether students can express quantitative or only qualitative relationships; and how easy it is to learn the modeling conventions of the tool.

A growing body of empirical work has suggested such methods have helped make computational modeling accessible and effective (Clark et al., 2009; Penner, 2001). These successes, along with a growing desire to engage young learners in authentic science practice, has provoked international interest in integrating computational modeling activities into the standard pre-collegiate science curriculum (e.g., NGSS, 2012; OECD, 2015).

Common Difficulties in Computational Modeling Activities

Researchers and educators, however, still cite a number of barriers to effective enactment of model construction activities in the classroom. One of the most frequently cited issues is learners' difficulties expressing their ideas using the modeling tools provided, despite advances in usability. In one study with middle school students, Xiang and Passmore (2015) found that while programming in NetLogo was linked to productive, iterative scientific modeling cycles, "…limited programming proficiency decreased the efficacy of [model-based inquiry]." (p. 328).

Basu and colleagues (2016) explored the challenges learners encountered when building computational models to learn science. In the study, 15 students completed a series of 7 scientific modeling tasks using a visual, block-based programming environment in a one-on-one interview setting. Grounded content analyses yielded four main types of difficulties. Two are best described as task specific: *Programming* challenges related to syntax and the user interface of the tool, and *knowledge* challenges involved the content learners need to know to begin modeling tasks (see also Mulder, Lazonder, & de Jong, 2010). Others, however, are more generally related to conceptualizing and structuring models. *Modeling* challenges included learners' difficulties representing their knowledge through, for example, identifying system entities or component behaviors. *Agent-based thinking* challenges reflected student difficulties in thinking about complex systems in ways that are conducive to the type of modeling paradigm the programming tool supported—namely, thinking about how an individual agent (such as a fish) in a system behaves, and attending to connections between that agent behavior and the system's aggregate behavior as expressed through the simulation or related graphs.

These more general, modeling-related difficulties have been documented for decades (Soloway, 1986), and across modeling environments including flow diagrams (Riley, 1990; Doerr, 1996), agent-based environments (Louca & Zacharia, 2008; Basu et al., 2016), and mathematical modeling tools (Löhner et al., 2003). Even after instruction with a particular tool, learners still struggle to decompose and translate their understanding of target systems (Sins, Savelsbergh, & van Joolingen, 2005); in some cases, learning gains do not appear until several iterations of model development and use have occurred (Chin et al., 2010). These issues point to incompatibilities between the modeling tools made available to students, the organization of knowledge they are expected to develop, and the epistemic practices in which they are expected to engage—alignments that are still understudied (Louca & Zacharia, 2012).

Addressing students' modeling-based and paradigm-based difficulties does seem to support deeper science learning for students. Fretz and colleagues (2002) found that supporting the decomposition and planning of a model, articulation of the relationships to be encoded in the model, and analysis and evaluation of the model after it was constructed were tightly connected to learners' engagement in modeling practices. In a recent review, VanLehn (2013) argued that "Although giving hints and feedback on the models that students construct appears to be problematic, giving hints and feedback on *the model-construction process (i.e. "meta-tutoring")* has been shown in several studies to produce larger learning gains than instruction that uses the same modeling tool without the meta-tutoring." (p. 404; emphasis added). Thus, understanding how learners approach the analytic tasks of conceptualizing, decomposing, and translating to a modeling form is key for understanding how computational modeling can support science learning.

Epistemic Forms and Games: Building Different Models, in Different Ways

To gain analytic traction for examining learners' approaches to conceptualizing and expressing their models with a given tool, we turn to Collins and Ferguson's notions of *epistemic forms* and *epistemic games* (1993). Epistemic forms are representational structures—such as lists, tables, or graphs—that are constructed to organize, reflect upon, and expand knowledge. They are cultural conventions that are developed and shared by practitioners, and particular forms are developed over time to answer particular types of questions. Epistemic games are the ways of thinking one might engage in as they work to populate those structures. Collins and Ferguson identified three such broad classes of analysis supported by different epistemic forms: structural (supported by epistemic forms such as lists or tables), functional (causal maps or form and function analyses), or process analyses (trend analyses; systems dynamics models). Epistemic forms and games have been more recently termed "model types" and "modeling strategies" (White, Collins & Fredericksen, 2011), but here we have chosen to use the original terms to emphasize active construction of knowledge versus representing or communicating what is already known.

The notion that systems of representation differ in function is certainly not new. diSessa (2001) analysed how kinematics was changed after the advent of algebraic notation. Kaput, Noss & Hoyles (2002) explored how shifts in representational infrastructure—such as the movement from the Roman to the Hindu-Arabic numeral system—democratized access to intellectual activities such as arithmetic. Wilensky & Papert (2012) called these infrastructural shifts in the representation, conceptual content, and learnability of disciplines *restructurations*.

Agent-Based Models are one example of restructuration that has become particularly important in the K-12 science education space. Using Collins and Ferguson's framework, we can think of agent-based models as an epistemic form that specifically supports analysis of mechanisms in complex systems. To build an agent-based model, one must define the agents that make up a target system, along with rules for their behaviours and interactions. The models can then be executed to observe how those individual mechanisms work together to produce indirect, emergent outcomes. This offers a specific example of the two types of discovery identified in the introduction. The "empty spaces" an epistemic form makes available–the individuals and interactions that comprise a system–guide the discovery of modelers' tacit knowledge. Once populated, the form provides new information—feedback about how individuals and interactions create collective outcomes—which guides further discovery through exploration and modification of model elements (Grimm et al., 2005; Wilensky & Reisman, 2006).

Many arguments for the educational power of new representational forms focus on their learnability. Agent-based modeling, for example, has been identified as an especially useful modeling paradigm for novice science learners because it connects to learners' embodied experiences as individuals moving through a complex world (Levy & Wilensky, 2008; Danish, 2014; Dickes et al., 2016), and allows complex systems to be described in narrative, sequential ways (Wilkerson-Jerde, Wagh, & Wilensky, 2015; Sengupta & Wilensky, 2009). Considering computational modeling from the perspective of epistemic forms and games, however, emphasizes two slightly different points about the role of representational tools and structures in supporting scientific inquiry. The first is that "[t]he desired result of any epistemic game is the completion of a target epistemic form that satisfies the inquiry." The second is, "Each epistemic game produces a characteristic form… But the same form may be produced by more than one game." (Collins & Ferguson, 1993; p. 28-29)

The first claim, that different epistemic forms can be mobilized to satisfy the same inquiry, is well documented in the literature. Research has examined the *complementarity* of epistemic forms, most typically by comparing different students' reasoning processes as they work with different modeling tools. For example, Löhner and colleagues (2003) and Louca and Zacharia (2008) found that learners exhibit different types of reasoning when creating models of scientific systems using text-based and graphical (concept-mapping) languages. Some have argued that such complementarity can be leveraged to build a progression of modeling activities that increase the amount of content, degree of specification, or level of analysis over time (White & Fredericksen, 1990) – a method that has been met with some success (Mulder et al., 2011). More recently, research has suggested that complementary representational activities such as drawing or play-acting can help support inquiry using agent-based models (Danish, 2014; Dickes et al, 2016). This study extends this line of work by investigating the potential for such representational progressions to support the practice of constructing computational models.

Our analytic focus in this study lies with Collins and Ferguson's (1993) second claim—that the same epistemic forms can be generated by different types of epistemic gameplay. This suggests that when learners have difficulty creating models of a given form, it does not necessarily reflect an inability to use the form or a lack of knowledge. Instead, it may indicate that learners have engaged in a different epistemic game not aligned with the designers' intentions. The questions guiding this study are:

1. *To what extent does student engagement in epistemic games different from those intended influence how they engage with and learn from computational modeling?*
2. *What facilitation and supports enabled learners to engage in the intended epistemic games?*

Study Context and Methods

To better understand the role that epistemic games play in student learning during computational modeling activity, we analyze data from a two-week enactment of a computational modeling activity in two fifth grade classrooms using an integrated animation and simulation toolkit called SiMSAM (Wilkerson-Jerde, Gravel, & Macrander, 2013). This is an especially apropos context to explore, since students in these classrooms demonstrated a breadth of success and struggle with the activity—some created models that clearly represented target systems, others created models that did not align with our intended curricular goals, and yet others struggled to create models at all.

The SiMSAM Modeling Environment

SiMSAM is a web-based application that allows students to create stop-motion animations by using an external camera to capture successive photos of drawings or craft materials (Figure 1). Once an animation is created, students can crop objects from the frames of their movie to become programmable entities called sprites. These sprites can be dragged onto a simulation canvas, and can be assigned rules using a simple programming-by-demonstration and menu interface. Sprites can be assigned physical transformation rules such as to move, change size, or rotate; they may also duplicate, delete, or spawn other types of objects. Rules are applied to sprites conditionally, so that they happen either when sprites are alone, or when they bump into objects of a particular type within the simulation. For example, if a user wished to model precipitation and collection, they may create a simulation with three object types: clouds, raindrops, and puddles. They could program cloud objects to emit raindrop objects with some frequency (such as with a 50% chance during each iteration of the simulation). Raindrop objects could be programmed to move downward, and to delete themselves when they bump a puddle object. Puddle objects could be programmed to grow in size whenever raindrop objects bump into them.

[INSERT FIGURE 1 HERE]

SiMSAM was designed specifically to support learners in "discovering" molecular theory—in particular, aspects of kinetic molecular theory that are typically learning goals in the early middle grades. These include that matter is made of particles, those particles are in perpetual random motion and collide, and that the states and properties of matter can be described in terms of the distribution and behaviour of these particles. We sought to emphasize these properties of matter through modeling various "experiential unseens" (Gravel, Scheuer, & Brizuela, 2013) such as smell diffusion, evaporation, condensation, or sound propagation.

A full justification for the design of the tool and associated activities is provided in (Wilkerson-Jerde, Gravel, & Macrander, 2015). Here, we provide a brief overview. We expected drawing to encourage learners to create visual representations for both physical and invisible objects and processes that constitute a target system (Larkin & Simon, 1987). We expected stop-motion animation to support their attention to discrete objects and how they move over space and time (Chang, et al., 2013). Finally, we expected agent-based simulation to explore generalizable rules about the behaviours and interactions that different classes of physical object within the same

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target system exhibit (Sherin, diSessa, & Hammer, 1993; Wilensky & Reisman, 2006). Through these processes, we expected learners to elaborate their ideas about molecular phenomena through modeling their mechanisms—that is, the objects, behaviours, and interactions that comprise a target system—thus engaging in the types of "mechanistic reasoning" (Russ, et al, 2008) that is considered critical for deep understanding of molecular systems.

School and Participants

The curricular enactment reported here was conducted at an urban-rim public K-8 school in the northeastern United States. The school serves a population of students with a diversity of identified racial/ethnic, economic, and special needs backgrounds (59.7% Low Income, 18.5% Students with Disabilities, 30.5% First Language Not English, 2.7% Multiracial, 18.7% Hispanic or Latino, 15.7% African American or Black, 10.6% Asian, 52.3% White).

These demographics were reflected in the two grade 5 (ages 9-11) classrooms we worked with. Sixteen students were enrolled in each class; 14 and 15 students consented to participate in the study respectively. The classroom teacher was a prior collaborator with our research team, had attended a masters and certification program at the researchers' primary institution that emphasized a focus on student thinking in science education, and had experience with earlier versions of the SiMSAM tool.

Classroom Enactments and Data Collection

We enacted a two-week design-based (Cobb et al., 2003) curricular unit in each class that involved two cycles of modeling activity using the SiMSAM tool. The activities were adapted from existing work (Shwartz et al., 2008). They were counterbalanced so that one class started by modeling condensation and then moved to evaporation, while the other class started with evaporation and moved to condensation. We will refer to these classes as Class C and Class E respectively. The school operated on a modified weekly calendar, so that we met a total of 4 days per week and some class periods lasted 90 minutes while others lasted only 45 minutes. The total time spent on the curricular enactment was a little over 8 hours.

For both classes, the sequence of activities was the same (Table 1). Students were introduced to a launching question: either "Why does a cold bottle of soda become wet on the outside?", or "What happens to puddles on a hot day?". On the first day, students discussed the question as a class, and then worked in small groups to create drawings that illustrated their ideas using templates. The small groups had been arranged by the classroom teacher, and five in each classroom participated in the study. On the second day, they created animations using craft materials and critiqued others' productions. On the third day they created simulations, and on the fourth they viewed and discussed simulations as a group. The second week followed a similar, slightly accelerated sequence of activities around the question each group had not already explored.

[INSERT TABLE 1 HERE]

We video recorded all whole-class and small-group discussion, screen captured students' interactions with the SiMSAM software, and saved all digital and physical artifacts for analysis. Videos were then synchronized with on-screen activity, and transcribed for analysis (Figure 2).

[INSERT FIGURE 2 HERE]

Methods of Analysis

Above, we identify three objectives we sought to support through modeling with SiMSAM. These are that students would create visual representations of visible and invisible objects through drawing, that they would attend to the movement of those objects across space and time with stop-motion animation, and that they would explore generalizable behaviors and interactions through computational modeling. In the background section, however, we questioned whether providing a given epistemic form, such as agent-based modeling, was sufficient for supporting expected learning goals. The same epistemic form, we noted, can elicit different epistemic games—thus, perhaps, engaging learners in different forms of reasoning than intended. The design conjectures outlined above assume that students will be playing a particular type of epistemic game, focused on the physical elements that make up a system (including molecules) and their behaviors and interactions. We call this the "entities, movements, and interactions" (EM&I) game, and expected that this game would support student reasoning about the physical mechanisms that underlie evaporation and condensation as molecular phenomena. As we show, however, students have many ways of creating animations and simulations. Not all include a focus on physical elements, but are still reasonable ways to make use of the epistemic forms provided in order to describe the target system.

Our research questions as stated above focuses on the relationship between the epistemic games learners play while actually constructing models using the SiMSAM tool, and the degree to which they are engaged in our intended learning goals, detailed above. Therefore, we conducted two strands of content analysis, focusing on videos of student group work during the animation and simulation phases of each modeling cycle during the unit. First, we analyzed students' digital productions and their talk to explore the extent to which they were *engaged in the EM&I game*—that is, whether they focused on representing entities, movements, and interactions within the target system. We found that two types of student group conversations in particular shed light on students' epistemic gameplay. The first were moments when groups strategized about the nature of the models they would like to construct, which typically occurred when they first began to work on creating an animation or simulation for a given modeling cycle. The second were any moments during which students referenced the modeling environment (and hence, the epistemic form) directly: noticing differences between the animation and simulation modules of the environment, or describing characteristics of particular representational types ("Movies tell you when it's the end"). This becomes clearer in the vignettes.

Second, to explore the degree to which each group accomplished our *intended goals*—reasoning about mechanism through iterative model-based inquiry—we conducted a content analysis of students' talk and expressed models. Transcripts from animation and simulation phases of each modeling cycle were divided into 5 minute intervals. Each interval was coded for evidence of (1) engagement in *reasoning about mechanism*, using a simplified version of Russ and colleagues' (2008) framework; and (2) engagement in *model-based inquiry,* using an adaptation of categories from Schwarz and colleagues (2009). We code for evidence of these two forms of engagement because they were the ones the activities were specifically designed to support; more generally, these are regarded as especially difficult and important goals of model-based inquiry activities (e.g., Danish, 2014; Dickes, 2016; Schwarz et al., 2009; Sherin, diSessa, & Hammer 1993). Since most exchanges that are given a code are shorter than 5 minutes, this analytic method over-represents the duration, but not the presence, of assigned codes. Nevertheless, we argue that this is an appropriate method for getting an overview of students' day-to-day work given our interest in the conditions under which mechanistic reasoning and modeling practice emerge. The method is described in more detail in Wilkerson-Jerde, Gravel, & Macrander (2015); Dickes

(2016) also argues strongly for the appropriateness of using Russ et al's framework to analyze student reasoning about complex systems.

A timeline presenting these codes was generated for each group; in this paper, the three timelines corresponding to in-depth vignettes are presented in full and the rest are summarized. Each row in the timeline indicates a modeling code that can be applied to a five-minute interval of talk. Each modeling code identified in a given interval of talk must also be assigned a mechanism code, indicated in the timeline by shade: the lightest shade indicates *describing phenomenon* and darkens for each of identifying *setup conditions*, *entities and properties*, *behaviors*, and *interactions* (darkest shade). For example, if a student says "we should show water vapor with blue dots", this would be coded as *representation* (modeling code) of *entities* (mechanism code; medium grey shading of box). If a student says "Clouds don't hold water, they are made of water. So, we should make the water molecules attach themselves to the clouds instead of making the clouds get bigger," this would be coded as *revising the model* (modeling code) based on *interactions* between water molecules and clouds (mechanism code; block shading of box). We describe a group as engaged in our intended modeling and mechanistic goals for the activity when we found evidence of them reasoning about *interactions*, and when we found evidence of their engagement in model *revision*, *empirical testing*, or use for *explanation and prediction* (Table 2). We used the presence and absence of these "intended" codes to define progress across days of the modeling activity.

[INSERT TABLE 2 HERE]

Findings

We report findings in two parts. First, we present comprehensive content analyses of all ten participating student groups. We then present three vignettes reflecting the breadth of student approaches to the activity. These vignettes were selected as particularly rich examples of three patterns observed. In the first, the group's epistemic gameplay was well-aligned with our intended use of the provided forms. In the second, the group's epistemic gameplay was not initially well-aligned with intended use, but became so with facilitator support. In the third, the group rejected the intended epistemic game. Throughout the vignettes, all student names are pseudonyms, and all classroom facilitators are marked with an asterisk.

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Overview of Content Analyses

First, we present a summary of content analyses for each of the 10 participating groups (Table 3). The summary indicates whether we found evidence that students engaged in what we consider to be aspects of *reasoning about mechanism* and *modeling practices* that we were particularly interested in supporting. These are instances of reasoning about mechanism that focus on interactions between entities, and modeling practices associated with evaluating, revising, empirically testing, and constructing explanations or predictions with the model—reasoning that has been found in prior work to be difficult to foster during classroom modeling activity. We also identify whether the predominant *epistemic game* played by each student group during each phase of the activity was our desired game, focusing on elements, movement, and interactions (EM&I).

For example, Group 1 in Class C was identified as exhibiting at least one of the listed modeling practices during the animation and simulation tasks in Cycle 1. However, we did not find evidence that this group attended to interactions within the system, and we did not find evidence that they played the EM&I epistemic game during these tasks. In contrast, we found evidence that Group 1 in Class E reasoned about mechanistic interactions, engaged in the desired modeling practices, and played the EM&I epistemic game. We will present three vignettes focused on groups for which we found low (Class C, Group 3), medium (Class E, Group 4), and high (Class C, Group 4) levels of representation in these categories over the course of the curricular unit. First, we note a few general trends that emerged from the summary analyses.

[INSERT TABLE 3 HERE]

Some clear trends emerge when reviewing our data in summary. First, across both modeling cycles, we found that evidence of student engagement in our intended goals increased as students transitioned from animation to simulation. This supports the main assumption driving our work, that *in general*, building computational models supports structuring knowledge (e.g., mechanistic reasoning) and fostering reflection and refinement (e.g., modeling practices). Second, we found that students did engage in multiple epistemic games when generating models; not all of which were aligned with our intended goals. Third, when groups were engaged in the epistemic game we intended to support, we found more evidence of modeling and/or mechanistic reasoning than when they were not. This pattern holds both across groups (when comparing groups that did and did not engage in the EM&I epistemic game), and within groups (when comparing tasks in which the same group did or did not engage in EM&I).

The summary analysis also supports our conjecture that students' engagement in our intended EM&I epistemic game, would encourage the types of modeling practices and reasoning about mechanism that we sought to support. Indeed, 7 of the 10 groups presented either created their models using the intended epistemic game from the beginning of the activity, or took up the intended epistemic game over the course of the unit. Furthermore, we found that 8 of the 10 groups showed "progress" in the activity—that is, engaged in more modeling and mechanistic reasoning over time. Of the two exceptions to this pattern, one, Class E Group 2, initially adopted, but then explicitly rejected the EM&I epistemic game. This case is presented in more detail in the next section. The other exception, Class E Group 1, engaged in the EM&I game for the duration of the activity. However, they misinterpreted the assignment: during the second task focused on condensation, they created a model of evaporation in a new context. In doing this, the group re-implemented representations and rules for scientific mechanisms they had already identified, they did not engage in new conversations or inquiry about molecular theory.

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An Example of Well-Aligned Epistemic Game

First, we present a case that strongly supports the conjectures that advocates of computational modeling for science learning put forth: that computational modeling can help learners discover scientific principles by structuring, elaborating, and reflecting on their understandings of the world. Miles, Kenny, and Raul were part of Class C, which began the modeling unit with the Condensation prompt, "When I take a cold drink out of the refrigerator, it becomes wet. What happens?". When the class discussed the prompt together, a few theories emerged: that the bottle had ice on the outside that had begun to melt, that water escaped through the cap from inside the bottle, and that water from the surrounding air was sticking to the bottle. This group agreed that the water is deposited onto the bottle by some kind of fog. They noted that sometimes when you open a freezer, you see a bit of fog or steam fall from it into the air, and that before a bottle becomes wet it has a flat cloudy film. The group disagreed about what the fog is comprised of, although Kenny surmised it was made of what he called evaporation: "Miles said that there's fog around it, I disagree and agree because I agree about the fog part because maybe the evaporation around it make, um, makes the fog."

The next day, students were told to create an animation that reflected their group's consensus about how a cold bottle of soda became wet over time on a hot day. Kenny, recalling the group's discussion from the day before, suggests that the group agrees about "fog" surrounding and sticking to the bottle (even though they disagreed about what the "fog" is made of). He quickly proposed representing that consensus element for the group using a tuft of cotton from the craft materials that he and other members of the group brought back to the table.

Excerpt 1, Planning for an Animation of Condensation

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Kenny. Raul, so we were thinking that, since you know, since we agreed on like, there's coming fog onto it, right? That's what we all agreed on. We thought, that we could, that this [*holds a small tuft of cotton*] could be fog and then it could slowly be coming down [*moves cotton down to table*]. And then like only little bits of it, but then after a while more and more.
Miles. What are you cutting right now?
Kenny. The um the Coke bottle.
Raul. We should put like every picture a little bit farther and then keeps [*moves a piece of cotton rigidly, simulating stop motion*]
Kenny. And then at the end, yeah yeah. Dude, that's what I was saying, yeah.

In this way, from the earliest stages of conceptualization, this group began playing the EM&I game. They selected tufts of cotton, objects that could be moved independently from one another, to represent fog. In the excerpt above, this is evident in Kenny's use of terms like "it" and "little bits" in his description (lines 13,14). This description is then taken up by Raul, who further discretizes the motion of the fog by demonstrating their motion as clear, separate steps. The group proceeded to add many such objects to their animation, and moved them each a small bit in every frame (Figure 3).

[INSERT FIGURE 3 HERE]

Since the group had focused on discrete objects and their movements when creating their animation, they had no difficulty selecting and moving those objects into the simulation environment. They selected the soda bottle, a single tuft of cotton, and a puddle of water (which they wanted to add as condensation gathers and drips down the bottle) as the object types they imported into the simulation module. Within the first ten minutes of the simulation-focused class session on Day 3, this group was already discussing how they hoped to program these objects using the modeling environment's facilities:

Excerpt 2, Creating a Simulation of Condensation

Raul. So the fog is coming and then its gonna go away. [*Kenny begins a movement rule*]
Miles. Wait no lets do it to interact actually cuz the fog goes on the coke bottle and then goes out after [*Kenny moves the fog object closer to the bottle object*].
Raul. Dude put it where it was.

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[*the students argue over whether to make the object move or interact; the teacher joins the group and asks what they are trying to do*]
Miles. We're trying to like move it and then hit the coke bottle and then come back
Kenny. We want this [*drags a fog object toward the coke bottle object*] and then when it hits it, it just stops [*leaves puff object on soda bottle*] and then we're gonna keep on adding more and then we're gonna put that [*gestures to puddle*] down there [*gestures to bottom of soda bottle*] and then after that were gonna make the white things disperse.
Raul. Yeah and then they go back.
Kenny. Yeah, disperse.

This excerpt reflects the kind of student talk that were coded for high levels of mechanistic reasoning and modeling practice in our broader analyses. The students are focusing on the specific physical interactions that together form causal chains that constitute the target system. They are also comparing what they hope the behavior of the model to be—in which some "white things" (fog, or water particles in the air) "disperse", or move randomly in order to dissipate—to their expectations of the world, and revising their rules accordingly.

There are two points of note here, both of which connect directly to the ways that agent-based modeling and the EM&I game are expected to support learning. First, the students' shift in focus from the behaviors of entities to their interactions ("let's do it interact actually because the fog goes on the coke bottle and then goes out after", lines 12-13; "it just stops", line 19), and then their eventual focus on "dispersion" (lines 21, 23)—happened right after Kenny opened the rules menu, and Kenny read the "interact" option from the screen. Second, Kenny's subsequent desire to make fog objects "disperse" caused the group to consider random motion and select the "wiggle" option to show the movement of their fog objects (Figure 4). It seems, then, that this group's well-aligned epistemic gameplay within the SiMSAM environment supported, and may have even prompted, this group's "discovery" of the random motion of particles.

[INSERT FIGURE 4 HERE]

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These two characteristics—random motion and interactions between objects—remained priorities for the group throughout the rest of the unit. The group did not experience difficulty creating their second animation or simulation of evaporation, and indeed used many of the same programming features that they'd discovered and put to use during their first modeling activity. Below, these aspects of molecular theory persist as the group explained their second model of evaporation, which used a particulate model of water with random motion to describe evaporation and the water cycle, to a facilitator:

Excerpt 3, Explaining a Simulation of Evaporation

Kenny.	So the steam is pretty much the evaporation. The steam is like the evaporation. The steam is the blue stuff.
Raul.	The steam is like, fake. The steam is like, invisible
Brian*.	Its like invisible? Okay so if I could zoom in. Say I'm so small I can see what's going on inside the puddle, right? What's going on inside the puddle, when you said it boils up, what's happening?
Kenny.	Inside, inside the puddle what's happening is the heat, its hitting the water and then you know when you put um, water in a pot and it starts to boil. The steam is actually the evaporation going into the air. But then eventually you can't see the steam when its boiling because eventually, um it, um, it combusts and goes away into the air so it can stay there, because, yeah.

Again, this excerpt reflects talk that was found to represent deep mechanistic and deep modeling engagement of the sorts we sought to support with this activity. Miles, Kenny, and Raul are describing how several elements of the target system interact, stringing together long chains (and loops) of causation. And, they are relating their model to other situations in which similar processes—heating and evaporation of liquids—occur. We present a detailed content analysis timeline of this group's engagement during the curricular unit in Figure 5.

[INSERT FIGURE 5 HERE]

An Example of an Ill-Aligned, Yet Productive, Epistemic Game

It was not always the case, however, that students took up our intended epistemic game. In our next case, a student group first reluctantly adopted, and then eventually rejected, the EM&I

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epistemic game. Mariah and Ava preferred to focus on modeling target systems in terms of phases that unfold temporally, rather than the objects and interactions that comprise the system. This was first evident when they began to plan their drawn models to explain what happens to puddles on a sunny day, on the very first day of the unit.

Excerpt 1, Creating Drawings of Evaporation

Mariah	Yeah I was gonna go like this, like step 1 and then draw raindrops and then like a puddle at the bottom, and then a line Step 2 and then the puddle will be just there by itself, step 3 and then it will show the puddle a little smaller and then maybe like um - you know how when something smells it has squiggly, like squiggly lines out of it, it's evaporating and then I'm gonna draw the sun over that.
Ava	So you want to draw like the steps of like the puddles?

Mariah and Ava translated their sequential representation of events into animation rather easily. While they used some discrete craft materials to represent elements of the system—blue pompoms to represent rain and cotton tufts to represent clouds (Figure 6)—they did not discretize elements in their representation of evaporation, which was the main focus of the activity.

Excerpt 2, Creating an Animation of Evaporation

Mariah	Okay okay. Have some blue showing [*adjusts blue pompoms in cotton cloud objects*]
Ava	Yeah don't make it like obvious that its showing, just make it like a little. Alright that should be good enough for it. Just take three [*takes three photo frames of the set up*]. Alright thats good thats good. Thats good. Now we need to show
Mariah	The sun is still there so [*removes the sun*]
Ava	And then the puddles go away [*removes the puddles*]. The next one is where–
Mariah	[*gasps*] We didn't show the puddles shrinking though.
Ava	Yeah but we're already showing the evaporating thing so it doesn't matter. So now we should take away all the blue–
Mariah	And now the sun is gone. And it's going to start raining.

[INSERT FIGURE 6 HERE]

Unlike the first group of students who clearly articulated how single elements in their animation would move per frame, this group articulated what elements and phenomena should be represented in each frame ("and then the puddles go away", line 12; "And now the sun is gone", line 16), and took multiple photos of each set-up in order to make sure the viewer had enough time to observe each phase (line 9).

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We would expect that Ava and Mariah's playing of this different epistemic game—focusing on sequential phases, rather than objects and motion—might introduce difficulties when they transitioned to the simulation environment. In the next excerpt, however, we find they recognized that some aspects of sequential phases, such as adding and removing objects at different times, was difficult to encode using the provided modeling tool—that is, their epistemic game was ill-aligned with the provided epistemic form. This led the group to revise their epistemic gameplay.

Excerpt 3, Creating a Simulation of Evaporation

17	Mariah	Mr. B! Um we're trying to make these [*gestures to puddle object*] after these [*gestures*
18		*to raindrops*] go. So after these go away, we want the puddles to appear. But we just
19		realized that it's not like the video so can you do that?
20	Teacher*	After those go away, you want the puddles to appear.
21	Mariah	Yeah cause its raining, then the puddles
22	Teacher*	Okay I see what you're saying. Um I don't think so... at least not that I know of.
23	Mariah	So then the whole thing has to go together?

Mariah and Ava quickly noticed that the tool is "not like the video" (line 19), and that the "whole thing has to go together" (line 23)—that is, all of the elements that are part of the system must be represented on the screen at the same time. Instead, transitions between system states had to result from behaviors and interactions exhibited by those objects.

After this realization, Ava and Maria quickly adjusted to create a simulation that featured raindrops that moved down toward a puddle. To demonstrate that water was both collected into and evaporating from the puddle, they defined two interaction rules: one deleted a raindrop when it bumped the puddle, and at the same time the puddle emitted a discrete evaporation "squiggle" object when it was bumped by a raindrop. During this process, they further clarify with the teacher the nature of agent based modeling, confirming that each object acts independently—that is, if there is a rule that droplets should delete when they bump into a puddle, only the triggering droplet would be deleted and not all droplet objects. Soon after this excerpt, Ava and Maria began to engage in deeper modeling practices, including revising the model to better reflect real systems.

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For example, like the first group, they introduced random motion to their simulation to show that there is water in the air everywhere, not simply over bodies of water (Figure 7).

[INSERT FIGURE 7 HERE]

Ava and Maria's final simulation reflected both random motion and a particulate model of matter, two of the goals of our activity. It was also adopted as a consensus model that was further refined during whole-class discussion. However, upon starting the second cycle of modeling, Ava and Maria again began conceptualizing their model by playing the sequential phase epistemic game. When planning their animated model, both articulated distinct step-by-step frames. Maria suggested "we could do like we did with the thing, like one step, two step, three step, four step, like we did with the um clouds." Ava elaborated what system elements each step may or may not include, "when we play it, it will look like when it's not that cold, the next thing its like there's water, there's beads of water outside of it."

Furthermore, when Ava and Maria moved to the simulation task during their second cycle of modeling, they did not modify their approach to satisfy the constraints of the system as they did before. Whereas in the first modeling cycle, Ava and Maria cropped distinct physical elements on the system (raindrops, puddles, clouds), in the second modeling cycle, they cropped entire frames from their animation (a dry soda bottle in a cooler, a dry soda bottle, a soda bottle with droplets on it). When it was time to assign those objects rules, Mariah suggested the rules should make particular objects (that is, particular frames of the sequential animation they had constructed) visible or invisible.

Excerpt 4, Creating a Simulation of Condensation

Mariah	This moves and we could like shrink this [*shrinking a frame object*] down to like a super small size so like nobody notices. So when it bumps it, it'll delete.
Ava	But why would it move? In reality Coca cola bottles don't move like this
Mariah	Cause how else is it gonna, oh you know what we could do, we could–

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Ava	Hold on wait wait wait
Mariah	If I bump something. Can I show you? We can delete it after and you can do it if you want
Ava	Hold on, if I bump something what?
Maria	If I bump something–
Ava	Hold on, don't don't I'll do it
Mariah	If I bump something, when I bump, where's the one with the water droplets? [*two dry coke bottles that were on screen show up*] Just go back. I'm gonna explain it to you okay first. So we're gonna have that [*soda bottle with no droplets*] over on top of that [*soda bottle with droplets*]. We're gonna have that go over that and what I'm trying to say, so if something, we could put, we could do this and shrink it down to like super miniature size so nobody notices, or we could do that cause that's not showing up and make this go up is a command, so it and this should be really close to it, so it moves only a little and then that would be like a before and this would be like an after - you get what I mean?

Here, Maria has devised a strategy to subvert agent-based modeling's focus on objects and interactions and instead reproduce the sequential phase approach that they have preferred when conceptualizing models. Ava recognizes the approach as inconsistent with the epistemic game the students were encouraged to play in class, noting that "In reality Coca-Cola bottles don't move like this" (line 26). Mariah continues to describe how rules within the system can be used to show "a before…and an after" (line 41) rather than physical interactions, including by having an object delete (line 29) or shrink to a barely noticeable size (lines 24-25, 38-39), and placing objects on top of one another so that only one is visible (lines 36-38). This meant that Ava and Maria did not have the opportunity to reflect on their model using the affordances of agent-based modeling, and we did not find much evidence of deep engagement in mechanistic reasoning or modeling practices in their talk during this modeling cycle. However, we are wary to suggest Ava and Maria did not engage in useful inquiry during this time, only that it may not have been reflected within the tools we developed with our specific goals in mind.

[INSERT FIGURE 8 HERE]

Facilitator Support to Shift from an Ill-Aligned to Well-Aligned Epistemic Game

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Like the group in the first case presented, Ryan, Sergio, and Luis were in Class C, and started with the condensation modeling task. Very early into the initial drawing activity, these students began to describe a system much like the water cycle, in which water is transferred from one location to another through condensation into clouds, and released via precipitation (in this case, onto the cold bottle that becomes covered in droplets). This description of steps is similar to those we observed with Ava and Mariah, and reflected a sequential phase epistemic game, rather EM&I. This conceptualization of the condensation model as a series of sequential phases continued the next day, when the group planned their animation.

Excerpt 1, Planning an Animation of Condensation

1	Ryan	So I first think that we should make a picture of the glass of water. And then we show
2		the ice going into it. And then we show you know nothing happening to it. And then,
3		and then the water comes down, and then the ice kind of starts you know, kind of
4	Brian*	So if you're gonna do that what do you need in terms of stuff? You need something for
5		ice cubes, you need something for water
6	Ryan	Mhm we need something for the fog
7	Brian*	For fog or ice on the outside.
8	Ryan	And then we need for the kind of water on the outside

[INSERT FIGURE 9 HERE]

Ryan suggests the use of "pictures," (line 1) what we interpret as frames, to show the sequential phases described earlier. The animation the group produces (Figure 9) emphasizes temporal sequence, changing what materials and objects are featured from frame to frame, and including a note indicating "The End". As the group moves from their animation to constructing the simulation, however, they struggle to identify what objects should be cropped. They understood that the simulation environment would allow them to animate objects with rules, but noticed that in their animation, no objects actually exhibited motion.

Excerpt 2, Identifying Objects for a Simulation of Condensation

9	Ryan	What moves, what moves? Okay okay, let's just see what moves. Nothing moves!
10	Luis	Dude you zoomed it too big.
11	Sergio	Okay.

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12	Ryan	What moves?
13	Ryan	I don't really think anything moves.
14	Sergio	Ya I don't think anything moves.
15	Luis	This is gonna be hard.
16	Ryan	Yea, I don't think anything moves.

We interpret this to mean that no isolated objects move in the group's animation, and therefore it did not make sense to crop anything. We are careful to note that describing scientific processes in terms of phases or scenes is not necessarily a productive characterization or faulty epistemic move. However, it is not an epistemic game that is well aligned with agent-based modeling as a form. Because of this, the group struggled during the first simulation activity and did not generate a working computational model during this modeling cycle.

Remembering this, the classroom teacher offered explicit guidance to this group during the second modeling cycle. This guidance focused on how to construct animations that could more easily be turned into simulations.

Excerpt 3, Planning an Animation of Evaporation

17	Ryan	How about, let's just start with a puddle?
18	Luis	How about a water vapor cloud?
19	Teacher*	So remember, you guys have got to use materials to show this stuff happening. So if
20		you just draw a cloud on there, it's never going to move. So if you want to show a cloud
21		moving, you need an objects. Like the, like a puff ball or something.
22	Luis	We can use the eraser.
23	Teacher*	But, you can move the puff ball.

[INSERT FIGURE 10 HERE]

This time, the group did not struggle to identify what objects should be cropped to become programmable entities. They quickly identified and imported, the puddles, blue pompoms to represent water vapor, a cluster of white pompoms to represent clouds, the sun, and the house as objects for the simulation. The classroom teacher continued to support the group as they learned to specify the particular interactions they wished to represent using the environment.

Excerpt 4, Creating a Simulation of Evaporation

24	Teacher*	ok, so you want to make some droplets coming out of the puddle?

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Ryan	And once it like it hits it then it disappears.
Teacher*	Once it hits what?
Sergio	The cloud.
Teacher*	oh ok. Do we want to make the clouds bigger so that you can– [*positions cloud objects so they are in the path of the droplet objects*]
Ryan	Yea.
Teacher*	Ok.
Luis	Yea, that's pretty good.
Ryan	Then when it hits it, the clouds are gonna like get bigger.
Teacher*	Oh wait sorry, say that again Ryan?
Ryan	When it hits it's, um, it's gonna get bigger

The patterns we observed in student talk during the second modeling cycle, when the group had been provided explicit encouragement to play the physical object game when conceptualizing and designing their model (lines 20-21, 23), reflected more of the mechanistic reasoning and modeling practices we had planned to support. Ryan, Luis and Sergio were no longer stuck wondering what objects were valid to include in their model. Instead, they debated how particular interactions between objects should be represented so that they best reflected the students' understanding of underlying processes. For example, these students debated whether vapor objects should make clouds grow bigger—suggesting the water went "inside" the cloud, but perhaps also inaccurately suggesting the cloud was a container that was filled—or make them duplicate, to show that water was "added" as a new part of the cloud itself. This depth of conversation, we argue, is difficult without the need to specify understandings in the way imposed by the SiMSAM tool.

[INSERT FIGURE 11 HERE]

Discussion

There is growing international interest in integrating computational modeling activities into the standard pre-collegiate science curriculum (e.g., NGSS, 2012; OECD, 2015). However, learners struggle to translate their scientific ideas into modeling languages (Basu, 2016; VanLehn, 2013), which reduces the epistemic power of this type of activity (Xiang & Passmore, 2015).

Drawing from Collins and Ferguson (1993), we conjectured that a major cause for such difficulties is a misalignment between the *epistemic games* learners play, and the *epistemic forms* a given modeling activity is designed to support. In this study, we explored this conjecture by examining the degree to which epistemic games mediate students' engagement in and learning from computational modeling activity.

We analyzed data from a study in which two fifth-grade science classes worked to create agent-based computational models to discover the particulate nature of matter. Agent-based modeling has been shown to support deep engagement in reasoning about mechanism and modeling. However, it requires a very particular type of epistemic game that we call the "elements, movements, and interactions" (EM&I) game. In general, groups that played this game exhibited progress toward discovering the intended content goals, and engaged in valued scientific practices, which groups that played other games did not. We illustrated this finding with three in-depth vignettes. In the first, learners easily played EM&I and constructed sophisticated, mechanistically rich models of molecular theory. In the second, learners slowly took up EM&I and advanced their understandings as a result, but then rejected EM&I for a different epistemic game which arrested their progress toward our intended learning goals. In the third, learners who initially did not play EM&I struggled to create any model at all; however, after their teacher redirected their attention to focus on the EM&I game, they produced a working simulation and began to engage in deeper modeling and mechanistic reasoning.

Together, these results suggest a strong relationship between epistemic gameplay and discovery learning through computational modeling. It is expected that modeling languages will work as epistemic forms to make evident what aspects of a scientific system need to be "discovered" (populated) during a given modeling exercise, and to organize those aspects in ways that promote further inquiry. To populate these forms, however, requires learners to be familiar with, recognize the utility of, and engage in the appropriate epistemic game. In terms of complex systems reasoning, our findings suggest that some students may benefit from explicit support in considering the elements, behaviors, and interactions in a system both before and during exploration and construction of agent-based models. Indeed, one reason for the success of complex systems interventions that employ complementary representational activities (as done in Wilkerson-Jerde, Gravel, & Macrander, 2015; Danish, 2014; Dickes et al., 2016) alongside agent-based modeling may be that these activities provide such scaffolding for appropriate epistemic gameplay. Additionally, our data featured several instances of students strategizing about and commenting on the limitations of their modeling tool; learning to attend and respond to such conversations may prove a fruitful line of future research on proper facilitation of model construction activities.

Our curricular activities and the SiMSAM tool were specifically designed to provide students explicit support in playing the EM&I game. The participant sample was only 26 students. And as with any design-based research project, a number of additional factors are likely to have influenced the patterns: the culture of our partner classroom valued scientific explanation and argumentation, and the presence of the research team in the classroom meant students had more support than they would have otherwise. Thus, our empirical findings, and the applicability of the underlying theory, should be examined in other contexts. We note, however, that we would expect the likelihood that learners will engage in unintended epistemic games to *increase* in absence of these supports; that this happens is a central part of our argument in this paper.

A major implication of these findings is that there should be a shift in how computational modeling environments are described, studied, and utilized in the classroom. Currently, researchers and designers focus on the *epistemic forms* provided for computational modeling—their learnability, the degree to which they connect with learners' intuitive knowledge structures, and how well suited they are for particular content. Correspondingly, studies focus on the effect of presence or absence of these epistemic forms on learning. However, our findings suggest that learning is mediated not only by the epistemic form provided, but also the *epistemic game* learners choose to play. Thus it is just as important, if not more, to attend to whether learners engage in the intended epistemic game when using a given modeling tool as it is to attend to whether they have access to the tool itself. Indeed, our own findings suggest that even if learners understand and have successfully engaged in a particular epistemic game, this does not mean they will continue to play it every time they are provided with the corresponding tool.

Conclusion

A pioneer of discovery-based learning methods, Seymour Papert's main thesis was "that children can learn to use computers in a masterful way, and that learning to use computers can change the way they learn everything else." (p. 7, 1980) This study demonstrates that children can learn to use computers in a *number* of masterful ways—*each* of which accomplish different goals, and can change how they think and learn about core scientific concepts. If we are to seriously understand the nature of discovery in discovery-based learning, we should investigate not only whether the presence or absence of particular tools can support learning, but also how students themselves make use of those tools in service of their own pursuits.

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Table 1. Schedule of classroom activities during computational modeling unit.

	Class C	**Class E**
Day 1 (45 m)	Introduce/Draw: *Why does a cold bottle of soda become wet?* 	Introduce/Draw: *What happens to puddles on a hot day?* 
Day 2 (90 m)	Animation, Gallery Walk	
Day 3 (90 m)	Simulation	
Day 4 (45 m)	Whole Class Review	
Day 5 (45 m)	Introduce/Draw: *What happens to puddles on a hot day?*	Introduce/Draw: *Why does a cold bottle of soda become wet?*
Day 6 (45 m)	Animation, Gallery Walk	
Day 7 (90 m)	Simulation	
Day 8 (45 m)	Whole Class Review	

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Table 2. Summary of Mechanism and Modeling Codes. Code descriptions are adapted from Wilkerson-Jerde, Gravel, & Macrander (2015).

Code Set	Code	Description	Intended
Mechanistic Reasoning	Describing Phenomenon	Providing examples of the phenomenon without linking them together or with a model; brainstorming ideas, relationships between ideas, and experiences with the target phenomenon.	
	Identifying Set Up Conditions	Attending to the conditions and components of the target phenomenon; considering spatial and temporal arrangements; considering states of entities in the target phenomenon.	
	Describing Entities	Consideration and identification of the objects/things relevant to the target phenomenon; consideration of their properties and representations.	
	Describing Behaviors	Consideration of the behaviors of the entities—e.g., how they move, why they move—with a level of entity by entity description and detail.	
	Describing Interactions	Consideration of the interactions between entities, the range of possible results of those interactions, and connections between individual entity behaviors and multi-entity interactions and/or observable effects.	X
Modeling Practices	Referencing Past Experience	Referencing some experience with the target phenomenon used to either propose, call into question, confirm, or refine some aspect of the model.	
	Representation	Symbolizing entities, behaviors, interactions, and other aspects of the model (e.g. creating a specific term/name/icon for something).	
	Explicit Selection	Decisions about what to include as elements/components of the model; evidence of a field of elements/components from which they chose.	
	Evaluating With Respect to the World	Considering the model from the standpoint of personal experiences and perceptions of smell in the known (to the participant) world. Evaluation is directed to the model, specifically	
	Revising the Model	Refinement, addition, pruning, or reorganization of aspects of the model (e.g., setup conditions, entities, behaviors, interactions).	X
	Empirically Testing the Model	Within the model, enacting of an empirical test to explore a dimension of the model; extending the model to a new context or new conditions.	X
	Using the Model to Predict or Explain	With a version of the model, a prediction of another context or an explanation of a context related to the model, using the model and described behaviors and interactions.	X

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Table 3. Summary of analyses for all 10 student groups in the study. Black shading indicates we found evidence for engagement in intended types of mechanistic reasoning (*Describing Interactions*) and modeling practices (*Revising the Model, Empirically Testing the Model, and Using the Model to Predict or Explain*) for a given day of activity. Gray shading indicates we found evidence for engagement in only one dimension. The text "EM&I" indicates we found evidence that the group was engaged in the "Elements, Movements, and Interactions" epistemic game. Groups identified as making progress exhibit movement from lighter to darker shades.

		Cycle 1: Condensation		**Cycle 2: Evaporation**	
		Animation	**Simulation**	**Animation**	**Simulation**
Class C	**Group 1**				EM&I
	Group 2			EM&I	EM&I
	Group 3 (Case 3)			EM&I	EM&I
	Group 4 (Case 1)	EM&I	EM&I	EM&I	EM&I
	Group 5			EM&I	EM&I

		Cycle 1: Evaporation		**Cycle 2: Condensation**	
		Animation	**Simulation**	**Animation**	**Simulation**
Class E	**Group 1**	EM&I	EM&I	EM&I	EM&I
	Group 2		EM&I	EM&I	EM&I
	Group 3	EM&I	EM&I	EM&I	EM&I
	Group 4 (Case 2)		EM&I		
	Group 5				

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Figure 1. Screenshots of the animation (left) and simulation (right) interfaces of the [Name] software. Objects are programmed using a combination of menu options and demonstration.

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Figure 2. Students worked in groups of 2 or 3 (left). Students' small group conversations and on-screen activity were synchronized to assist with analysis (right).

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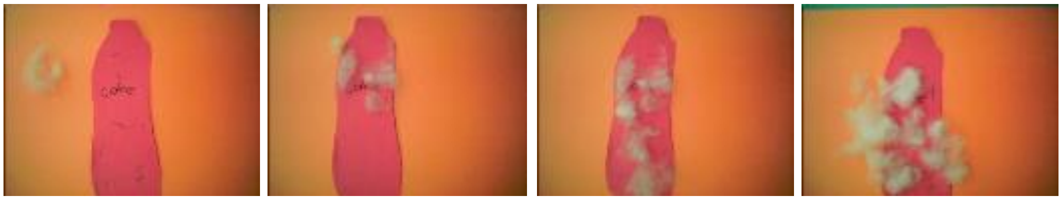

Figure 3. Group C2's condensation animation featured small tufts of cotton to represent "fog".

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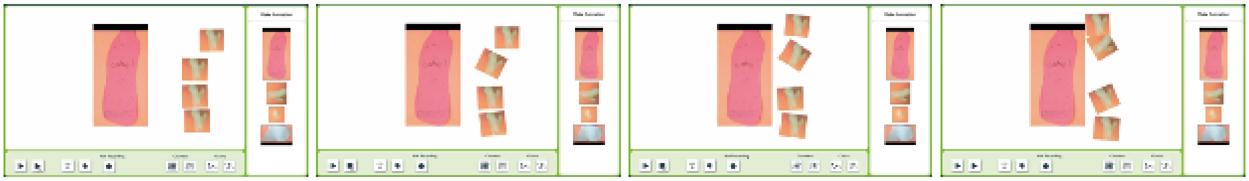

Figure 4. Kenny, Miles and Raul's simulation featured particles that move randomly and stick to the bottle.

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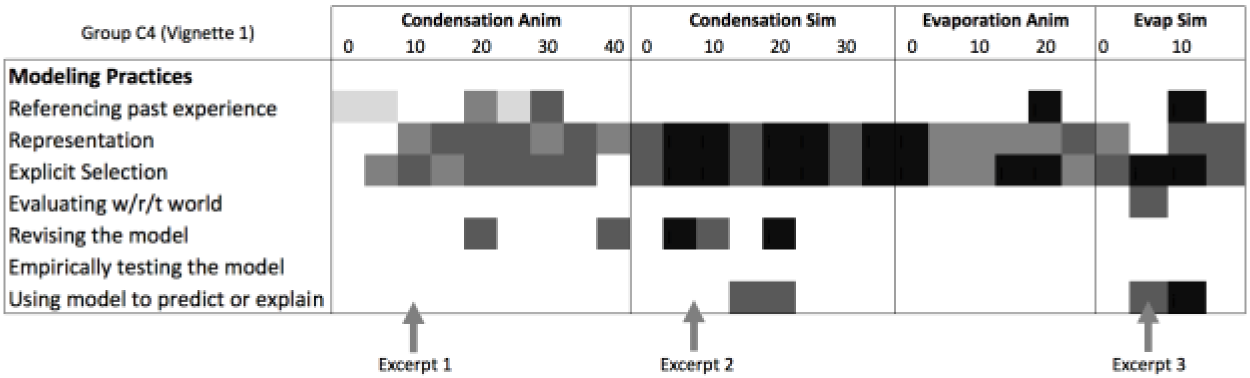

Figure 5. Timeline of mechanistic reasoning and modeling practice codes for Vignette 1. Timelines are described in the Methods of Analysis section of this paper.

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Figure 6. Ava and Maria's animation used discrete objects, but reflected phases that unfolded in sequence.

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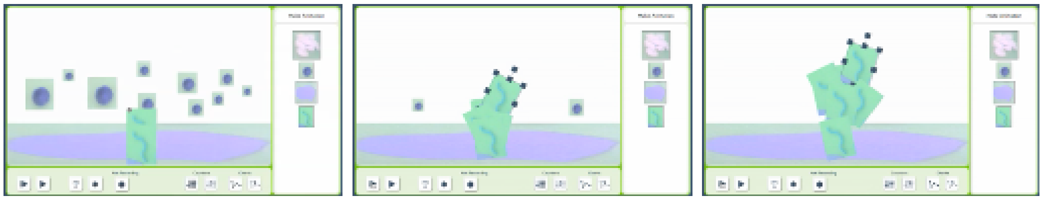

Figure 7. Ava and Maria’s simulation featured interactions to show that water collected into and emitted from the puddles, and random motion of water vapor “squiggle” objects.

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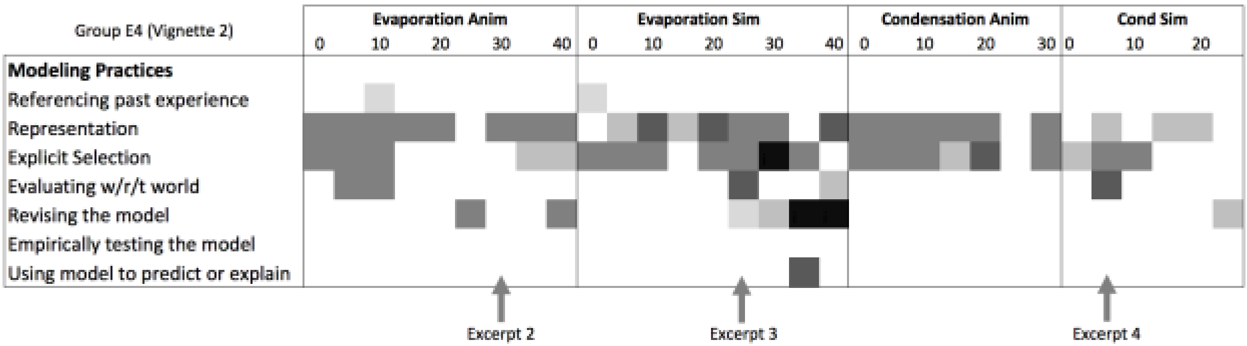

Figure 8. Timeline of mechanistic reasoning and modeling practice codes for Vignette 2.

Figure 9. Ryan, Sergio, and Luis' animation included frames illustrating condensation, evaporation, and collection on a cold glass.

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Figure 10. Ryan, Sergio, and Luis' second animation featured discrete, moving objects.

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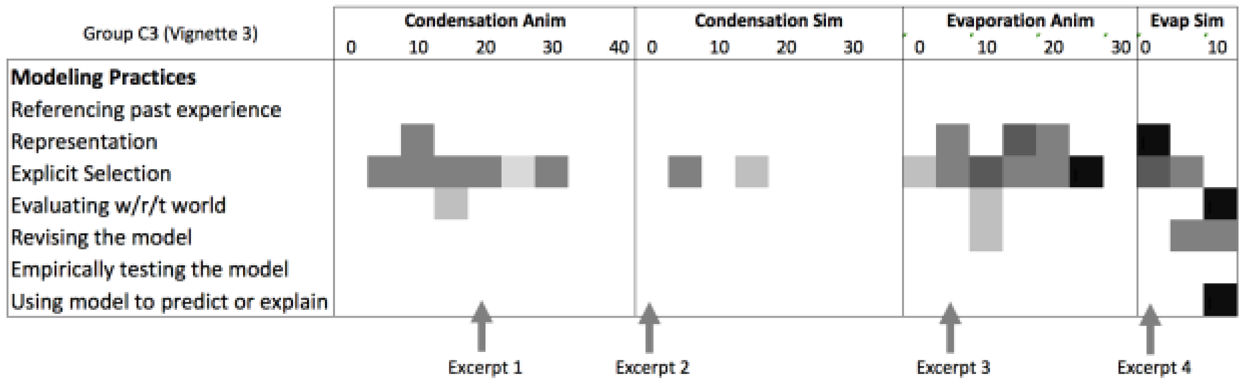

Figure 11. Timeline of mechanistic reasoning and modeling practice codes for Vignette 2.