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Exploring Computational Modeling Environments as Tools to Structure Classroom-Level Knowledge Building

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Abstract. Although computational modeling is noted as a powerful way to engage students in scientific knowledge construction, many studies focus on individuals or small groups. Here, we explore computational modeling as an infrastructure to support classroom level knowledge building. We present data from a two-week study where two fifth grade classrooms modeled evaporation and condensation. We focus our analysis on one group that experienced success with the activity, and another that struggled; these groups' intended models emphasized random motion and aggregation respectively, two important but complementary molecular behaviors. Both groups' ideas were incorporated into a collective model designed in consultation with the entire class. We show that computational modeling (1) often required explicit support, but when leveraged productively (2) served a *representational* role by supporting the elaboration of student ideas about physical mechanism, and (3) served an *epistemic* role by allowing students to compare, synthesize, and build on other's contributions.

Keywords: scientific modeling; classroom discourse; science education; computational modeling; knowledge building; epistemic games

In this paper, we are concerned with *computational modeling*. We define this to be the practice of iteratively constructing, refining, and thinking with representations of scientific systems that are encoded as computer-executable code. By engaging in these practices, 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 (Papert, 1980; Penner, 2000). With proper facilitation and support, computational modeling is generally understood to be an effective way to engage learners in model-based inquiry and knowledge construction (van Joolingen, de Jong, & Dimitrakopoulou, 2007; Wilensky & Reisman, 2006). Here, we argue that it can also be transformative at the *classroom* level by providing a framework for students to collectively contribute, evaluate, and synthesize scientific ideas through the production and refinement of shared playable artifacts. In this way, computational model construction environments can serve as analogs to the types of argument and explanation focused knowledge-organizing tools often used to support classroom learning communities (Scardamalia & Bereiter, 1994), though considerably different in structure and focus.

To illustrate, we present a multiple case study from a computational modeling unit about condensation and evaporation enacted with two fifth grade science classrooms at an urban-rim public school in the Northeastern United States. We focus on two groups within one classroom, though these groups reflect a wider collection of student experiences during the unit. As we will show, these two groups developed models drawing from different experiences and explanations of condensation and evaporation, and their models foregrounded complementary scientific mechanisms. One group was quickly successful in building a working model, while the other struggled to do so. The scientific mechanisms illustrated by these two groups' models, along with contributions from other groups in the classroom, were consolidated into a collective model (constructed by facilitators in consultation with students) that offered more explanatory power than any one group's model alone. This collective model was then taken up by the classroom to reason about other, related science phenomena. We argue that for this classroom, computational modeling (1) often required explicit support, but when leveraged productively (2) served a *representational* role by supporting the elaboration of student ideas about physical mechanism, and (3) served an *epistemic* role by allowing the class to compare, synthesize, and build on each other's contributions.

Background

There is a growing body of work focused on computational model construction as a learning activity (for a recent review, see VanLehn, 2013). This work has shown that with proper support and facilitation, engaging in model construction can help students make sense of complex scientific phenomena, and productively engage in model-based inquiry. However, the focus of this research has typically been on the conceptual learning of individual students, or on practices and discussions that emerge among pairs or small groups of students as they models. For example in a recent study, Xiang and Passmore explored students' engagement in cycles of model-based inquiry supported by ABM programming while working in pairs (Xiang & Passmore, 2015). This focus on individual or pair model construction persists across research group and modeling environment (e.g. Löhner, van Joolingen, Savelsbergh, & Hout-Wolters, 2005; VanLehn, Wetzel, Grover, & van de Sande, 2016 to mention a few). Similarly, studies designed to explore *scaffolding* to support model construction activities often focus on students working "separately and individually" (Basu, Sengupta, & Biswas, 2015, p. 307) or in pairs (Fretz et al., 2002). Our own explorations of model construction activities thus far have similarly focused on discussion and understanding of specific scientific content among small groups (Wilkerson-Jerde, Gravel, & Macrander, 2015).

Work that has investigated the role of computational models and simulation at the *classroom* level, on the other hand, typically does not focus on the computational model itself as a site for knowledge construction in the same way as studies focused on content learning or modeling practice. Instead, they focus on providing classroom communities with *access* to computational models, to serve as fodder for discussion or other collective activities. One line of work has explored the development of public galleries or immersive environments where students can interact with, organize, and create of computational data and artifacts (Van Joolingen, De Jong, Lazonder, Savelsbergh, & Manlove, 2005). Another line of work has investigated how teachers can orchestrate productive whole-group discussion, argumentation, and sense-making using pre-constructed simulations as representational tools to inform and test theories about scientific phenomena (Berland & Reiser, 2011; Hmelo-Silver, Liu, Gray, & Jordan, 2015). Yet others investigate the relationship between individual or small group work with computational tools, and collaborative engagement in discussion, juxtaposition, and sharing of resulting artifacts (Hegedus & Moreno-Armella, 2009).

The work reported in this paper lies at the intersection of these two literatures. It explores whether or how computational model construction activities themselves can serve as a site for community knowledge building. Looking across several projects focused on knowledge representations to support learners' engagement in the epistemic practices of science, Sandoval and colleagues (2000) separated projects into two classes. One class of knowledge representations, which they called "epistemic representations", focused on the construction and organization of student arguments and explanations. The other, which they called "discipline-specific models", focused on engaging learners with conceptual aspects of a discipline (for example, by interacting with or constructing their own representations of content in probability or chemistry). They argued that these two classes were distinct, but suggested that "[a]n interesting line of research… could be to consider how [discipline-specific models] might communicate epistemological ideas more explicitly" (p. 39). We conjecture that discipline-specific representations and other representational infrastructures not specially designed to make argumentation explicit *can* nevertheless serve as a site for students to co-construct scientific knowledge and learn productive epistemic moves in the process, with proper scaffolding and facilitation.

Theoretical Framework

To investigate our conjecture, we leverage Collins & Ferguson's (1993) theory of *epistemic forms* and *epistemic games*. Epistemic forms are representational structures that can be populated by practitioners to organize, reflect upon, and expand their knowledge—such as lists, tables, or graphs. Epistemic games are the ways of thinking that allow them to effectively populate and make use of those forms—for example, reasoning about what might be reasonable axes on a graph, or recognizing and developing methods to fill in missing data in a table. Epistemic forms and games are cultural conventions that are shared by communities of practice, and particular forms are well-suited to answer particular questions. A time series graph, for instance, can make evident temporal and covariational relationships that might otherwise be difficult to identify.

Collins and Ferguson illustrate the notion of epistemic forms and games by invoking the periodic table. The table was an effort to organize an as-of-yet unstructured collection of elements whose physical and chemical properties were difficult to understand. It revealed regularities within spatially proximate groups of elements, and empty spaces in the table predicted the existence of other undiscovered elements. As additional discoveries were made, scientists modified the table, eventually recognizing its relationship to the electron shell structure of atoms. This example highlights four key aspects of epistemic forms: They can be populated with what 'players' know now; they make evident what players may need to know and investigate; they can be modified and contributed to by other players; and they reveal links to other representations and domains.

Bielacyzc and colleagues (Bielaczyc & Ow, 2014) build on these notions of epistemic forms and games to describe *multiplayer epistemic games*. These are games in which epistemic moves are distributed among a community, such that population of the epistemic form serves as an infrastructure to bring differential expertise together. They argue that a major part of building communities of learners is to explicitly scaffold their shared participation in epistemic games, and that knowledge emerges at the level of the whole from interactions among players. Classrooms and infrastructures designed to support multi-player epistemic games emphasize student work as a driver for curricular content, enable epistemic games to be played as a collective, and support epistemic moves and games through explicit pedagogical moves.

Here, we posit that computational modeling environments can serve as epistemic forms to support multi-player epistemic games in the classroom. Specifically, we argue that they can support the comparing, testing, and synthesis of one another's proposals regarding what physical mechanisms underlie certain scientific events (such as evaporation or condensation, in our case). The elaboration and comparison of proposed mechanisms using computational models is commonplace in scientific practice (Chandrasekharan & Nersessian, 2015; Grimm et al., 2005). And, agent-based models have been identified as a "model type" or scientific tool alongside concept maps, tables, lists, and mathematical formulae (NGSS, 2013; White, Collins, & Frederiksen, 2011). Therefore, the question that motivates this paper is: **What is the potential for computational modeling environments to support knowledge building at the classroom level?**

Study Context

The data we present in this paper are drawn from design-based research study conducted with two classrooms at a public, urban-rim K-5 school in the Northeastern United States. The school serves a population of students with a variety of identified racial/ethnic, economic, and special needs backgrounds; this was also reflected in the classrooms we worked with. However, the gender balance of our focal classroom in this paper is deserving of comment. Only 5 of the 15 students who consented to participate in the study identified as girls (one student in the class did not consent to data collection); members of the groups we focus on in this paper all identified as boys. Given that the research was conducted in a public classroom during the school day, this imbalance is reflective of naturally occurring differences in student populations and does not reflect a self-selection or participation bias in the research or activities. We focus our analysis on two groups from one class (Figure 1). We video recorded all whole-class and student group interactions, screen captured students' interactions with computers, and collected all written work for analysis.

Figure 1. Disperse Group (left), Water Cycle Group (center). A projector was positioned in the front of the classroom (right), and was used to show animations and simulations for whole-group discussion.

The two-week enactment involved two modeling activities that are loosely adapted from activities developed for the IQWST and MoDeLS projects (Schwarz, Reiser, Acher, Kenyon, & Fortus, 2012), and connected to important science standards (Building and Using Models; Matter and Its Interactions; NGSS, 2013). In the first week, we introduced students to the launching question "Why does a cold bottle of soda become wet on the outside?". On the first day, students discussed the question as a class, and then created drawings that illustrated their ideas using templates (Figure 2). On the second, 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 sequence of activities around the question "What happens to puddles on a sunny day?".

As part of the SiMSAM project, we have developed a web-based integrated animation and simulation application that is used as the computational modeling environment during activities. With the tool, students can create stop-action movies using craft materials or drawings. Once the movie is created, they can crop objects from the frames of their movie to become programmable "sprites". They can then drag the "sprites" onto a simulation interface and program them through programming-by-demonstration and a collection of menu options to define behaviors like interaction, duplication, or random motion.

The two groups we choose to focus on for the purposes of this paper represent cases drawn from a larger multiple case study (Stake, 2006). The quintain, or central shared phenomena, that the cases are chosen to shed light on concerns the ways in which students' group artifacts contribute, conceptually or materially, to an eventual collective product that is endorsed by the class as a community. We choose these two groups because they offer a contrastive illustration of this central question. The groups both constructed simulations that reflected different experiential knowledge resources – related to steam and weather – and that eventually contributed very different but equally essential elements to the shared classroom model. Second, they experienced varying levels of success working with the modeling environment. Together, the focal groups reflect two extremes of a diversity of approaches across the class as a whole, in terms of knowledge leveraged, focal mechanisms expressed, and levels of success.

Figure 2. Templates used for drawing tasks (left), and animation (center) and simulation (left) interfaces.

Methods

Our analyses focus on (1) elaboration of student ideas, (2) the degree to which the tool supported students' articulation and revision of ideas, and (3) collaborative knowledge building through use of the tool. To identify student ideas, we used verbal analysis to identify what knowledge learners mobilized when making sense of prompts and activities. To investigate the nature of student engagement in relevant epistemic games, we attend to the degree to which their discussions and actions provide evidence that they are reasoning mechanistically (Russ, Scherr, Hammer, & Mikeska, 2008) and engaging in modeling practices (Schwarz et al., 2009).

Finally, to explore collective knowledge construction, we identified when artifacts (such as a simulation or representational convention), theories (such as the particulate nature of water), and vocabulary (such as use of the term "vapor") became taken up as shared by the classroom, and how much those artifacts, theories, or vocabulary were made possible or emerged through collective use of the modeling environment.

Results

In this section, we report on students' participation in constructing simulations. We will show that in both cases, the modeling environment offered students a way to externalize and elaborate their ideas. We then report the development and adoption of a collective model that featured contributions from several classroom groups. Throughout the results, we present transcript of group and classroom discussion. To make clear the role of facilitators in these discussions, when the classroom teacher or research staff (Michelle and Brian who are also authors on this paper) appear in transcript records, they are marked with an asterisk.

Dispersion Group

During the first activity, students were asked to explain why the exterior of a cold bottle gets wet on a hot day. While the three students' initial drawings had been quite different, Kenny had identified "fog" as a point of agreement across the drawings and this became a focus for the Disperse group's animation.

Kenny: So 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 cotton tufts*] could be fog and then it could slowly be coming down. And then like only little bits of it, but then after a while more and more.
Miles: We should put like every picture a little bit farther [*acts out steps with cotton tufts*]

Kenny described fog "coming down…like only little bits" and "after a while, more and more." Miles enacts how this description can be expressed using the stop-action animation format with craft materials, suggesting that in "every picture"—each frame—the bits of fog could move a little bit farther. From the drawings and Kenny's comment, we see emerging descriptions of "fog" as a discrete, scattered entity that moves gradually. We also note Miles' early adoption of gradual, discrete movement as the "epistemic game" he uses to populate animation as a form. The group's final animation showed tufts of cotton gradually moving toward and sticking to the Coke bottle, creating droplets of water on the bottle, and then scattering away from the bottle.

The next day, the group began to build their simulation using cropped images of a soda bottle and "fog" (cotton tufts). Kenny initially tried to reproduce the animation by programming cotton tufts to move toward the bottle. Miles, however, noticed that there was an option in the simulation environment to make objects *interact* with one another, rather than merely move. This option works by triggering only when two objects come in physical contact with one another within the simulation environment.

Miles: Wait no let's do it to interact actually, cuz the fog goes on the Coke bottle and then goes out after.

Edgar: Well the fog is coming and then it’s gonna, yeah, go away.
[*1.5 minutes later*]
Teacher*: What are you guys discussing?
Kenny: We’re trying to like move it [*toward the bottle*] and then hit the coke bottle and then come back.
Kenny: We want this and then when it hits it (coke bottle) it just stops and then we’re gonna keep on adding more and then were gonna put that (puddle) down there (at the bottom of the coke bottle) and then after that we’re gonna make the white things [*“fog” objects*] disperse.

Here, Miles suggests the “interact” feature is a more sensible representation for their purposes, since the group agrees that the point of contact between “fog” and the bottle is critical. Miles’ attention to the features he has available in the simulation, and their potential connections to the phenomenon the group is modeling, suggests continued alignment between the epistemic game he is playing and the form he is populating. Meanwhile, Kenny notes a behavior of fog that he wishes to illustrate in the simulation—*dispersion*, or a random scattering of particles. This scattering is programmed into the computational model as a slight random wiggle, so that “fog” objects meander toward the soda bottle, and then bounce against it to represent “sticking”.

The representation of “fog”, or water particles, moving randomly and “dispersing” persists into the second activity concerning evaporation. The group constructed a simulation in which “steam”, represented as blue dots, moves randomly between puddles at the bottom of the screen and clouds at the top. When asked to describe their construction, all three invoked notions of cooking, steam, and combustion:

Edgar: So the steam is pretty much the evaporation. The steam is like the evaporation. The steam is the blue stuff.
Miles: The steam is like, fake. The steam is like, invisible
Brian*: 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, it’s 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 it’s boiling because eventually, um it, um, it combusts and goes away into the air so it can stay there, because, yeah.

Throughout the Disperse group’s participation, there is evidence that they are leveraging knowledge of the behavior of fog and steam as substances that scatter, “disperse”, and “combust” to inform their model. These notions are easily translated over the course of a few days into random motion of particles in the simulation. This random motion, as we will see in the next section, becomes a major contribution to the class’ shared model.

Aggregation Group

When discussing what they wanted their group animation explaining condensation on a soda bottle to look like, Luis offered an early proposal. He suggested that on a hot day a cloud forms; then, that cloud “turns cold” so that it “could drop … ice” which would melt causing water to appear on the bottle.

Luis: So I thought, like, if it was a really hot day. So I thought this cloud would like form because like it might like like if if, cuz you know evaporation like it has like clouds. So then I thought if, the cloud turns cold it could drop like ice, if you put it back in the refrigerator, and then ice would be on it like you could see the ice, and then it would all melt for like the water to appear.

After several minutes of discussion, Ryan proposes this plan to the classroom teacher, and the group settles in to creating an animation featuring a sort of mini water cycle that carries water to the outside of the bottle:

Ryan: So we're gonna try to like, you know, just pictures of the ice and water just sitting there, and then the ice starts coming, and we're gonna try and say in like one sentence about you know, you know, it gets so cold it builds up ice.
Teacher: It builds up ice where?
Ryan: Builds up ice outside the glass.
Teacher*: Outside the glass
Ryan: Mhm, and then and then we, these little things are gonna be water droplets that's gonna start dropping and then after a while we're gonna make ice like on the table.

While it is unclear from the transcript alone that Ryan is echoing Luis’ idea of clouds, the resulting animation produced by the group aligns especially well with traditional descriptions of the water cycle. It featured an open glass that was filled with water, then filled with a cloudlike substance (represented with cotton), a movement of the cotton to the outside of the glass, and a releasing of blue drops from the cotton onto the outside of the glass.

Unlike the Disperse group, who generated their animation using small, discrete movements of objects, the Water Cycle group generated their animation using "scenes" that roughly corresponded to evaporation, condensation, and precipitation. While creating an animation from "scenes" is commonplace and makes reasonable use of the stop-action moviemaking tool, it did not set the group up well for agent-based modeling as an epistemic form. This first became evidence as started to decide what objects to crop in order to assign those objects rules to define their movements and interactions.

Ryan: What moves?

Ryan: I don't really think anything moves.

Sergio: Ya I don't think anything moves.

Luis: This is gonna be hard.

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 faulty epistemic move. However, it is not well aligned with agent-based modeling as a form. Because of this, the group struggled to generate a working model to illustrate their explanation. Remembering this, the classroom teacher offered explicit guidance on how to construct animations that could more easily be turned into simulations during the second activity in which students modeled evaporation.

Teacher: So remember, you guys have got to use materials to show this stuff happening. So if you just draw a cloud on there, it's never going to move. So if you want to show a cloud moving, you need an object. Like the, like a puff ball or something.

Luis: We can use the eraser [*to erase the pencil drawings*].

Teacher: But, you can move the puff ball.

After these explicit instructions and continued support from the classroom teacher, the Water Cycle group was able to create a working simulation to describe evaporation:

Teacher: Ok, so you want to make some droplets coming out of the puddle?

Ryan: And once it like it hits it (cloud) 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—[Ryan: Yea] Ok.

Luis: Yea, that's pretty good.

Ryan: Then when it hits it, the clouds are gonna like get bigger.

This time, the students readily describe behaviors and interactions among objects in their simulation, and relate those behaviors and interactions to the phenomenon they wish to describe. For example, Ryan proposes to model clouds as "droplet accumulators" that grow larger when they are hit by a droplet of water that disappears—ostensibly because it has joined, or gone inside of, the cloud. Like the Disperse group, the Water Cycle group's focus on clouds as collectors of water was sustained across both activities, despite their struggles with simulation as a representational form. After explicit instruction on how to play the appropriate epistemic games, they were able to operationalize this notion of cloud as a water collector by exploring interactions between droplet and cloud objects. By the end of the day, the group had decided to duplicate clouds, rather than making them grow, to show that droplets are added to rather than taken inside of clouds.

Development of the Collective Model

Toward the end of the evaporation activity, we projected the Water Cycle group's simulation to be discussed by the class. Students immediately began to interpret the simulation and make suggestions:

Sheree: I think it represents when the sun evaporates the water, um the clouds they start to make new ones because of the water vapor.

Sarah: But one thing I don't understand is when, when the droplets go up, the puddles don't disappear. So are you saying that the puddles are still there?

Miles: I think it's like the water droplets are just going straight up, and then it's [clouds] just gonna get bigger and bigger

We took note of students' suggestions, and brought a model that incorporated many of them into the Water Cycle group's simulation the next day (Figure 3).

The new model illustrated different group's ideas across both modeling activities: The notion of "droplets" or small, discrete representations of water had been adopted unanimously by the class; random motion was contributed by the Dispersion group; the notion of droplets adding to clouds was contributed by the Aggregation group; and other contributed behaviors were also featured.

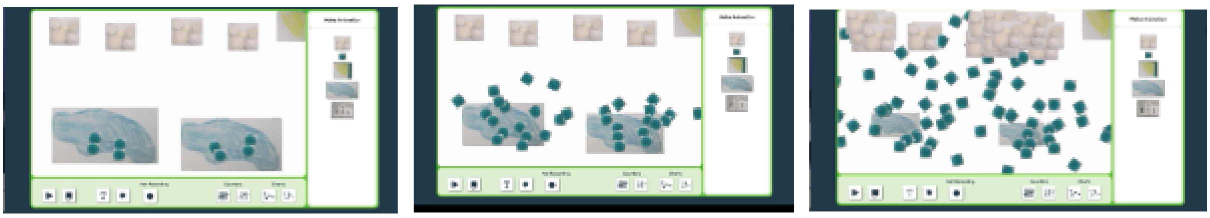

Figure 3. Simulation presented to students that combines random motion of particles (from Disperse Group), accumulation of water particles in clouds (from Water Cycle Group), and shrinking puddles that emit water particles (volunteered during discussion by another group in the class).

The class became excited when the model was presented, and their subsequent descriptions and analyses included combinations of mechanism that had been distributed across various student groups' simulations:

Michelle*: So I heard that a lot of people were sort of excited about this one. Does anyone want to talk about why? Maybe voices we haven't heard?
Luis: Because the water droplets are like going up and the puddles are shrinking.
Michelle*: And what do you think that represents that you agree with?
Luis: That, like, all the water droplets are like going away because the puddles are drying up.

James: Yesterday we couldn't get the puddles to go down, get smaller and the raindrops to go up. But in this one the puddles got smaller and she didn't have to place the things, it just you know.

Kenny: The sun rays go into the water, the water starts to boil, it goes into the air, it makes clouds, and it's evaporation. And it happens over and over again.

Sheree: Evaporation is when the sun takes water, and then it turns it into water vapor and then it turns it into a cloud, or adds on to a cloud.

There are two things to notice here. First, the students engaging with the shared simulation and making sense of it in the context of their own ideas (note Miles and Kenny's descriptions of boiling to describe the random motion assigned to a different situation, and Luis' interpretation of the edits to his own). Second, they attend to some of the unique affordances of computational models as a representational form, noting that interactions such as the puddles growing smaller without needing to do anything manually is preferable.

There is additional evidence that students took up this shared model and its main components: particulate models of water, random motion, and cloud-as-collector. In a follow up activity in which we asked students to explain why the water level of a heated covered beaker does not fall while the water level of a heated uncovered one falls quickly. All groups in this class created models with particles, random motion, and ideas about particles "eventually going to clouds" or entering the water cycle.

Conclusions and Implications

In this paper, we argued that computational modeling environments can serve as sites for collaborative knowledge construction, much like the collaborative concept mapping and diagramming tools that are common in communities-of-learners classrooms. We illustrated how two groups used animation and simulation infrastructures to externalize, elaborate, compare, test, and synthesize ideas about the mechanisms that underlie evaporation and condensation. These mechanisms were rooted in the students' existing knowledge, and contributed elements of a model that became taken up at the classroom level.

This work suggests specific supports for enacting computational modeling activities. The classroom teacher, when working with the Water Cycle group, explicitly and intentionally focused on *epistemic moves*—how the group was populating their animation in anticipation of converting it to a simulation—and not other aspects of their work such as content. The use of templates to structure student models, and the inherent modularity of computational models, made it especially easy for us to share, contrast, and combine students' ideas. This allowed students to recognize their own work and contributions within a new or different model. Developing norms for computational modeling and critique can also improve student motivation and learning from such environments. Research should extend beyond attention to individual and small group learning to see how computation can become part of the epistemic fabric of science classrooms.

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