Building consensus through modeling: A framework for the fitness of ideas in classroom science discourse

A qualifying paper

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Abstract

Scientists use argumentation, critique, and modeling to generate consensus around particular ideas. Students in science classrooms can be supported to engage in similar knowledge-building discourses. However, they often come up with idiosyncratic representations as they participate in these scientific practices. In this paper, we direct our attention to the dynamics of ideas as a lens to examine why certain ideas were taken up in knowledge-building discourses around condensation. Drawing from memetics, we present the Idea Fitness Framework (IFF), which identifies four selection forces that contribute to an idea's fitness in student modeling discourses. Using microgenetic and sociogenetic examples of how the forces operate in the classroom, we show how IFF operates as a dynamic system that helps to explain how consensus is reached among fifth-grade students in one class engaged in modeling the process of condensation using computational tools.

Science educators strive to balance the objectives of engaging students in the disciplinary practices of learning, as part of a knowledge building community (e.g., So, Seah, & Toh-Heng, 2010; Van Aalst, & Sioux Truong, 2011) and developing their understanding of canonical knowledge. These objectives align with the Framework for K-12 Science Education (National Research Council [NRC], 2012). Specifically, the framework aims to actively engage students in scientific practices (e.g., argumentation, model development, and using evidence as specified in Dimension one of the framework) and with the "fundamental questions" of the world (p. 9). The framework's vision is to prepare students for the education appropriate for the 21st century where they grow to be critical and knowledgeable of the scientifically and technologically rich world we live in (National Research Council [NRC], 2012).

Science educators are also aware that students often present ideas incongruous with the intended canon. Moreover, some of these ideas take hold in a group and become a stable focus of their discussion, particularly when students' ideas drive the classroom scientific practices. When classroom scientific practices like argumentation and modeling emerge from students' ideas, rather than predefined conceptual goals, science educators face the challenge of coordinating the objectives of students developing facility in these practices and, at the same time, learning the desired concepts in the established body of scientific knowledge.

In this paper, we are interested in uncovering the mechanisms by which ideas take hold in a group and how consensus is reached among students. Understanding such mechanisms can help educators with coordinating the aforementioned objectives by motivating guiding moves to structure class activities.

Knowledge Building Discourses as Means to Build Shared Practices

In a knowledge building community, members work together to refine their thinking using different "epistemic artifacts" (Sterelny, 2005) which can include models in many forms, or tools that help learners both conceptualize their thinking and advance the discussion in the classroom. An aim is that students begin to engage in the scientific practices of argumentation and modeling to construct knowledge about a phenomenon in question (Bielaczyc & Ow, 2014; Scardamalia & Bereiter, 1994, 2006; Zhang, Scardamalia, Lamon, Messina, & Reeve, 2007).

Members participate in science by contributing ideas, asking for clarifications, and defending their thinking, all the while building on their ways of understanding and relating to the phenomenon under consideration and the conversation at hand. During these *knowledge building discourses*, some ideas get taken up more readily than others, and in turn, students spend more time developing their thinking about them.

One of the challenges that teachers and researchers might face in engaging students in scientific practices as members of a knowledge building community is making students' ideas the drive for learning (Bielaczyc, Kapur, & Collins; 2013) and therefore encouraging students to reconceptualize science as negotiable and dynamic rather than strictly authoritative and static. Students must make their understandings accountable to their peers as part of a community as they learn scientific practices to build knowledge together (Ford, 2008; Manz, 2014; Scardamalia & Bereiter, 2006).

Negotiating ideas and building shared practices go hand in hand 'as ideas are considered resources for navigating activities' (Hall and Greeno, 2008, as cited in Manz, 2014). We draw from two lines of work examining how groups effectively build knowledge together to understand the dynamics of ideas: prior research on argumentation in science classrooms and the role of model-based reasoning in science learning.

Establishing Scientific Practices in a Knowledge Building Community

Argumentation is an essential tool for building knowledge in classrooms (Driver, Newton, & Osborne, 2000; Duschl, 2000; Manz, 2014). In particular, Manz (2014) emphasized the importance of situating argumentation in the activities in which members engage. Argumentation around ideas in a class designed to support knowledge building must take into consideration the conditions surrounding the material and social artifacts that students built as well as the students' evolving ideas. Manz also brought attention to the role of argumentation in stabilizing classroom norms. That is to say, argumentation around ideas with a purpose of building knowledge together furnishes what is taken-as-shared practices within that specific community of learners. This reconceptualization of argumentation as a tool for students to build knowledge redefines scientific practices to mean " 'scientific practice for students' if it is constituted by a classroom community for a function that is important in their scientific activity" (Manz, 2015, p. 575).

The literature on model-based reasoning locates learning in the iterative and ongoing process of building, communicating, and refining models that initially embodies students' ideas and experiences and eventually progress to generate new knowledge (Lehrer & Schauble, 2000; Louca, & Zacharia 2012; Schwarz et al., 2009). Nevertheless, for discourse around modeling and argumentation to constitute knowledge building discourse, students and teachers need to commit to progress towards common understanding that is satisfactory for all participants (Bereiter, Scardamalia, Cassells, & Hewitt, 1997). Knowledge building is then situated within classroom activities where students bring their conceptual resources and are able to grapple with the uncertainties and questions that emerge from the collective construction of epistemic artifacts (Manz, 2014).

Selection of Unexpected Ideas in Science Classrooms

It is a familiar yet curious outcome of supporting scientific practices that conversations around unexpected ideas can be sustained for long periods of time. When students bring in their conceptual resources and grapple with uncertainties, idiosyncratic representations become quite productive for students as they discuss and refine their ideas. These uncommon ideas and representations can also be taken almost infectiously by the students. For example, Wilkerson, Gravel, and Macrander (2015) studied the discourse of five middle-school girls engaging in a modeling activity focused on the question of how smell travels. They detail the birth of “oogtom”, a representational object invented by the girls that is “a combination of the words oogie and atom” (p. 13). The girls imagined an element of smell “oogie” and an element of matter “atom” intertwined to make one object and frequently referred to “Oogtom(s)” in their modeling discourses. “Oogtom” supported the girls’ mechanistic reasoning by helping them make predictions about their computational models built to describe how smell moves across a room.

Many treatments of the selection and movement of similar ideas place the individual’s mind at the epicenter of learning. For example, researchers on conceptual change have studied both the conditions that allow individuals to consider conceptions as well as their proclivity for attending to new conceptions. For ideas to be integrated into the “conceptual ecology” of the learner (Posner, Strike, Hewson, & Gertzog, 1982, p. 231), they have to be: intelligible so that their meaning is clear; plausible so far as they are consistent with other held conceptions; and fruitful in ways to suggest new forms of thinking or solve potential problems. Competing ideas also have to be dissatisfactory for new ideas to be considered (Posner et al., 1982). This framework attends to each individual learner to understand how they construct knowledge but does little to inform us how groups work together to reach consensus around new or unexpected ideas.

We are considering dynamics at the scale of the classroom community (Cobb & Yackel, 1996), but we take a complementary step to the treatment of classroom as a dynamic environment by adopting the ideas' perspective and looking at their dynamics. We ask:

What contributes to the persistence of certain ideas and the fading of others in classroom discussions? What influences the selection and propagation of some ideas over others?

Studying the dynamics of ideas shifts the focus from studying individual decision-making strategies to paying attention to interactional considerations surrounding the selection of ideas. This view takes the entirety of the community as a medium where ideas get selected, propagated, and refined. As we will show, this approach can be useful in understanding the mechanisms by which practices are taken-as-shared and the ways ideas and practices co-evolve in a classroom.

Research Context and a Preview of the Paper

In this paper, we look at students' interactions in a science classroom designed around modeling the phenomenon of condensation (Wilkerson, Shareff, Gravel, Shaban, & Laina, 2017). We present episodes where students discussed competing and often unexpected ideas and map the evolution and propagation of their contributions. We look at the dynamics of ideas; what ideas persisted and what ideas faded away, and what is the nature of those ideas to present the Idea Fitness Framework; a set of selection forces (described in detail below) that contribute to an idea's fitness in student modeling discourses.

Theoretical Framework

We draw from different theoretical traditions that have attempted to understand the persistence, mutation, and evolution of things and ideas among communities of individuals. This paper suggests that looking at the interactions of ideas and what ideas persist and how they evolve in students' conversation can inform us of the mechanism by which consensus is reached between students. Moreover, it can shed some light on how students engage in the practices of science while building from their own understandings and resources.

Research on Practices and Conceptual Understanding

Manz (2015) asserted that argumentation as a scientific community practice is situated, shared, and emergent from students' activities as they are grappling with uncertainty in the learning environment. It follows that students' ideas should not only drive the emergence of practices but also shape their goals as negotiated between members of a community. Designing modeling activities as part of a knowledge building community must thus take into account that students might face difficulties in translating their understandings into models (Basu et al., 2016 as cited in Wilkerson, Shareff, Laina, & Gravel, 2018) especially if students' ideas did not drive the need for such an activity.

Consequently, supporting model-based inquiry, "which engages learners in constructing models of a target system for which few details are explicitly provided," (Wilkerson et al., 2018, p. 37) call for particular considerations. It requires revealing students' conceptual understanding and at the same time allowing for conditions that facilitate their reflection on other competing representations to engage in creating, revising, and updating their models.

Memetics

Researchers have attempted to model the phenomenon of idea propagation by drawing on Darwinian processes by which genes get selected and passed on (Blackmore, 1999; Dennett, 1995; Harlow, 2014). Successful evolution in a Darwinian system requires three elements: variability, competition (or selection criteria), and means for propagation or heredity (Blackmore, 1999). Ideas, scientific or otherwise, have been considered to follow a similar evolutionary trajectory.

What is a meme?

To devise a unit of idea transmission, Dawkins (1976) coined the term "meme" to talk about a "unit of cultural transmission" (p. 189). Dennett (1999) later defined a meme as "an information-packet with attitude." These *information packets* include Internet memes as well as books, paintings, technologies, dressing code, and scientific ideas. While it is hard to define what exactly a meme looks like in a learning environment, researchers built their definitions of what a meme is. Yoon (2008) defined memes as "ideas found in the rationales that could have a differential effect on how many students would agree with another student's rationale" (p. 907) and used that definition to study students' understanding of genetic engineering concepts and applications.

The construct of memes allows researchers to think differently about what gets transmitted. Ideas do not only spread because they are useful, but also because they are memorable, or easy to understand, or pleasing. The memeticist Susan Blackmore (1999) pointed out that the nature of ideas and the ways they group and propagate together influence why some ideas get favored over others.

In this paper, we will concern ourselves with studying the considerations surrounding the spread of ideas: what influenced the selection and propagation of a particular contribution? This view takes the students, the nature of ideas, the class structure and activities, and any facilitative moves by the teacher or coordinators as conditions that could encourage or hinder the spread of students' ideas.

The Analytical Framework to Track the Evolution of Ideas in a Classroom

The classroom is a dynamic environment where students quickly build on each other's contributions. As a result, their ideas are continuously evolving. Saxe et al. (2009) studied how mathematical ideas travel in classrooms, and while they do not define a meme specifically, they described the genetic processes of how students' ideas last and change over the course of instruction.

A genetic perspective takes inspiration from Darwinian processes by implying that ideas or representational objects are not always faithfully replicated, instead they go through a continuous process of mutation and crossover to better address the questions and problems at hand. As a result, a new unintended function or form may emerge out of the continuous interactions of community members to solve local problems or arrive at a commonly shared understanding. In another study that implemented a genetic perspective, Saxe & Esmonde (2005) followed the shifts in mathematical function and form of “Fu” in the Oksapmin community and explicated the intricate relationship between these shifts and collective practices of economic exchange. The function of “Fu” shifted as a result of community members finding common grounds to negotiate fiscal transactions. These studies highlight the importance of situating our understanding of mutation of ideas in the environment that bred it. In addition, it hints at how consensus is reached in a community as an emergent phenomenon from solving individual coordination problems and subsequent interactions between its members (Saxe & Esmond, 2005).

In this work, we attend to the analytical considerations of situating evolving ideas rather than defined memes in discourse by borrowing from Saxe et al. (2009) and focusing our inquiry along two analytical strands: (1) a microgenetic strand that examines moment-to-moment constructions of representations as individuals negotiate and relay their thinking about the given phenomenon, and (2) a sociogenetic strand that focuses on the discourses among individuals and between groups as students work to convey their thinking. Both of these strands can intersect as groups negotiate meaning about a given representation. The two strands permit discovery of various mechanisms that were at play both at an individual level and on a group level. This is important when we ask how consensus is reached between groups of students where their individual members had different considerations and contributions about the phenomenon in question.

How Selection Forces Help us Understand the Persistence and Evolution of Ideas

We are motivated by initial observations in the classroom of how diverse ideas students brought to the modeling activity went through a process of selection; some ideas were taken up, others were not. To map the travel of ideas by the mechanisms of selection and propagation, we examine the memetic construct of *selection forces* acting on students' ideas during knowledge-building discourses. Yoon (2008) offered that both conceptual and social selection forces make some ideas more salient than others in a classroom. For example, Yoon identified a selection force on a group level and is based on social influence; "do as the smart students do" is a strategy that students consciously or unconsciously follow to select which ideas are best to adopt in class. Selection forces as a construct are generative with our model of the classroom as a dynamic system where emergent behaviors or practices occur on nested timescales and are continuously evolving (Lemke, 2000; Thelen & Smith, 1994).

This conceptualization allows us to locate shifts in students' thinking in the context where it occurred and still consider these shifts as a fertile ground for classroom-level shifts in building knowledge. To operationalize selection forces, we consider the entirety of students' contributions as our *selection pool.* The selection pool contains all available ideas to the students but is at the same time dynamic, contextual, and student dependent. For example, students engaging in a whole class discussion can pick up ideas from their peers as well as add to the pool from their own experiences, observations, and knowledge. While students in their own groups can sustain and engage their members' ideas, they might also enrich and add to it from a previous class discussion, or new lines of thinking about the phenomenon. In our data, these constitute verbal contributions as presented in discussions, paper drawings, videos, animation, and simulation models.

The Idea Fitness Framework

From a memetic perspective, selection processes are continuously happening in the selection pool and depend on how *fit* an idea is: fitness is the idea's ability to survive and evolve to gather consensus among students. Different ideas have different lifetimes. For example, on the first day, a student suggested that molecules inside a bottle come through the bottle and appear as water beads on a cold drink in an effort to explain how condensation happens. This contribution was presented again on the second day of activities but no other student picked it up. The idea that something inside the bottle came outside did not propagate beyond the second day in students' conversations, while other ideas about water sources from the bottle did. To investigate the lifetime of ideas, we situate this travel of ideas within a "dynamic between individual and collective activity" (Saxe et al., 2009, p. 210). This dynamic lies in individual and collective model construction as well as discussion and critique of multiple models.

We present a framework for selection forces to highlight what contributes to the overall "fitness" of an idea within classroom modeling activities, which we call the Idea Fitness Framework (hereafter IFF). Through analysis described below, we found four selection forces: Relatedness, Consistency, Generative Ambiguity, and Authority. Relatedness pertains to the idea's connection to other ideas or observations students have available. Consistency highlights the idea's compatibility with other ideas or observations. Generative Ambiguity extends the lifeline of ideas when they are able to carry more than one possible interpretation or understanding of the phenomenon. Finally, Authority incorporates the social positioning and perception of the participants. We conceptualize these forces as interactive complex selection criteria that could have differential outcomes in how prominent or otherwise depressed ideas evolve over the course of the class activities and their ability to spread from one student to another.

Methods

This study is part of a design-based research project that explores how middle school students engage in scientific modeling about molecular phenomena using SiMSAM (Simulation, Measurement, and Stop-Action Moviemaking). SiMSAM's stop-motion animation is constructed by capturing images from an external camera that the students can use to build a story of how they think the phenomenon works. The agent-based simulation feature gives the students the opportunity to apply predefined rules to objects from their animations to program their motion and their interactions with other objects on the same simulation canvas.

Participants

We report on data from a fifth-grade science classroom in a public K-8 school in the northeastern United States. The school serves a population of students from a diversity of identified racial/ethnic, economic, and special needs backgrounds. Sixteen students were enrolled in the class, and 14 students consented to participate in the study. The classroom teacher was a prior collaborator with our research team. He had attended masters and certification programs 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.

On the first day of the activity, we posed the question:

“When I am thirsty in the summer, I pull a cold drink out of the refrigerator and leave it on the counter. Before long, beads of water appear on the outside of the drink. How did the water get there?”

Over three class periods (~3.5 hours), students engaged in a sequence where they worked in groups to construct drawings, stop-motion animations, and agent-based simulations, interwoven with whole-class discussions about their evolving models for condensation.

The students experienced these tools for the first time and the facilitators presented a short demonstration at the beginning of each activity to guide the students on how to use the various options in the tool’s interface. The students presented their work in front of their classmates as a whole group and in gallery walks. Students’ written work, small group interactions, and whole-class activities were captured or video recorded and transcribed for analysis.

We analyzed the data according to the trajectory of the class activities and engaged in repeated viewing of video data (Derry et al., 2010) from the classroom intervention to construct *idea trajectories* which identified the following: the student who articulated the idea, whether the idea was taken up “as is” or modified, and when during the activity particular students articulated the ideas as shown in Figures 1. The purpose of this microgenetic analysis was to see what ideas students took up most often and which ones they did not, and how they talked about them over time. An initial analysis yielded a consensus forming between Boss King Fireballs (hereafter BKF, and members are Sarah, James, and Owen) and Slick Boss (hereafter SB, and members are Kenny, Edgar, and Miles) around the idea that water droplets came from water in the air. Members of each group had different ideas at the beginning of the class of how condensation worked. In addition, the members of the two groups, except in brief episodes, shared their thinking in every activity throughout the three days. This data gave us the unique opportunity to trace their thinking closely within their groups and during class discussions and presentations. The authors proceeded to do a secondary content analysis to detail how the members interacted with each other and their environment (Jordan & Henderson, 1995) in an effort to examine how they negotiated their ideas from a group-consensus perspective (the sociogenetic) and again how the seeds of the idea that condensation comes from water in the air was reached by each individual student (the microgenetic) (Saxe et al., 2009). Finally, we distilled the first and second analyses into general themes that describe what contributed to an idea's fitness, and those themes were applied to the data to yield the final list of selection forces and their definitions (Blackmore, 1999; Yoon, 2008).

It is important to mention that after the first step analysis, we noted students were picking up different aspects of their peers' contributions to build on or reject. While two contributions might, in essence, refer to the same idea according to our "reconstruction of students' situated cognition" (Welzel & Roth, 1998, p.30), the students often interpret them as two different offerings. As a result, we will often refer to *contributions* instead of *ideas* in our analysis to ground our thinking in what the student said and how that is being taken up by other students.

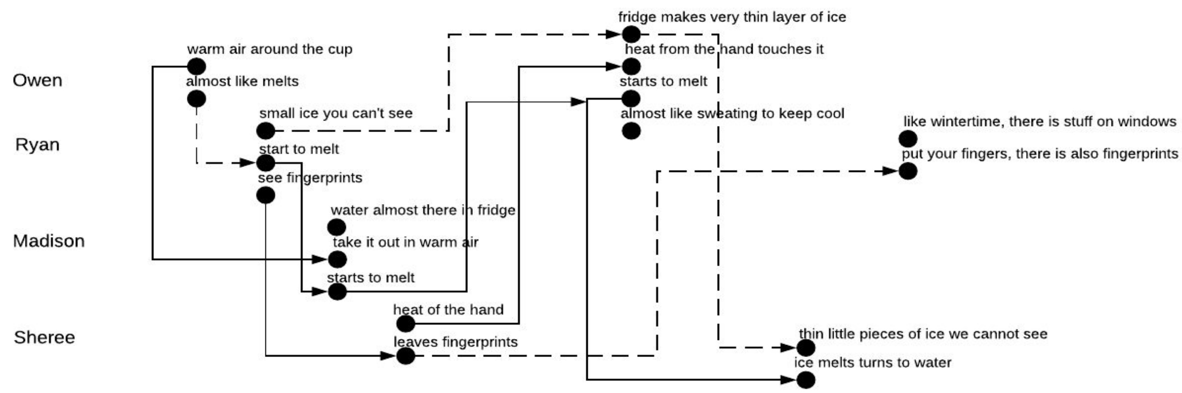


Figure 1: Example of mapping of the trajectory of *a thin layer of ice* during a whole class discussion. Each black dot represents an aspect of a student contribution. The dashed line indicates that this aspect was modified and picked up by another student. The solid line indicates that the same aspect was replicated in another student's contribution. To simplify mapping ideas, the beginning of the arrow indicates the last mention of a contribution and not necessarily the source of it, and the end indicates the next temporal mention. A contribution usually has vertically dots that represent the process of crossover. Students hold multiple ideas about the phenomenon from different sources.

We will detail episodes where members of each group worked together over their final simulations to highlight instances of how we distilled the forces and how they worked for the groups to reach consensus.

Analysis of Selection Forces Operating on the Trajectory of The "Water in the Air" Idea

Students' contributions built on each other and the same students presented multiple contributions to the phenomenon. Following a round of discussion on the first day, students were particularly enthusiastic about three central themes concerning the water droplets visible on the outside of the bottle: 1) water droplets came from difference in temperature, 2) a small “water cycle” took place around the bottle where some of the stuff in the bottle “evaporates” and then “condenses” on the bottle, and 3) a “thin layer of ice” forms on the bottle when it is in the refrigerator, and that melts when placed on the counter**.**

By the end of the third day of the activities, members of the BKF (Sarah, James, and Owen) and SB (Kenny, Edgar, and Miles) had similar contributions that condensation appears from *water in the air*. The members had a variety of ideas about the source of water, as will be discussed below, but none explicitly articulated that condensation comes from water vapor as BKF members presented, or from evaporation that is around us as SB members argued in front of their class.

From a memetic perspective, the *water in the air* competed with two other main ideas within these groups; *a thin layer of ice* championed by Owen in the BKF, and *water coming from inside the bottle to the outside* supported initially by Edgar and Miles in SB. The below sections will focus on contextual considerations and sociogenetic perspective to shed light on how this idea became favorable and attempt to describe the dynamics of the identified selection forces.

The Role of Relatedness in Constituting the Selection Pool

On the first day during a whole class discussion, the students contributed what they know and had experienced that relates to the phenomenon under consideration. These contributions constituted the selection pool. For example, students related the phenomenon to “stuff on windows” in wintertime, evidence of “fingerprints” on a can of soda, and the process of sweating, “almost like sweating to keep cool.” (refer to Figure 1 above)

Sarah was one of the first students to relate the question to a shared experience

Sarah You have, like if you go to Dunkin Donuts and get a drink. And then you walk, alright and then you have it and you walk outside and usually you put like a napkin over it, and then when it gets wet, it's like when heat condenses with... coldness, and cold, it, like, they don't really like go together well, so it sort of like separates. It's like olive oil and um like, in a vinaigrette or something like that.

Sarah immediately linked the observation stated in the question of beads of water appearing on the outside of the drink with her experience of going to Dunkin Donuts. You order a drink and then you receive it and then you walk outside. Sarah provided another important detail, that a person usually puts a napkin around the drink and that the napkin gets wet. Sarah’s use of the pronoun “you” and the word “usually” in her contribution suggests that she was communicating a personal experience that she assumes is common and relevant to her audience. Sarah paused to try to think how the napkin got wet: “heat condenses with … coldness.” There is hesitation in describing this mechanism, but she followed with *it’s like olive oil in a vinaigrette*. Two liquids that don’t really go well together according to Sarah. While she did not describe a particular mechanism for how the water appeared, she recognized a similarity to another phenomenon with which she was familiar, how a napkin gets wet around a Dunkin Donuts drink. Similarly, she related the observation of how oil in a vinaigrette behaves to a process that might explain the appearance of beads of water. The coldness of the drink and the heat of possibly the weather, as suggested in the prompt, perhaps don’t go well or mix.

Looking at the contributions selected in students’ discussions on the first day, Relatedness emerges as a force operating by introducing contributions that are related to students’ everyday experiences and observations.

Students also came with a variety of contributions that are not part of their observations and experiences and are perhaps cued from previous science classes. However, while these contributions were introduced into the selection pool in the early stages, their meaning had evolved, and some contributions were not sustained in later conversations.

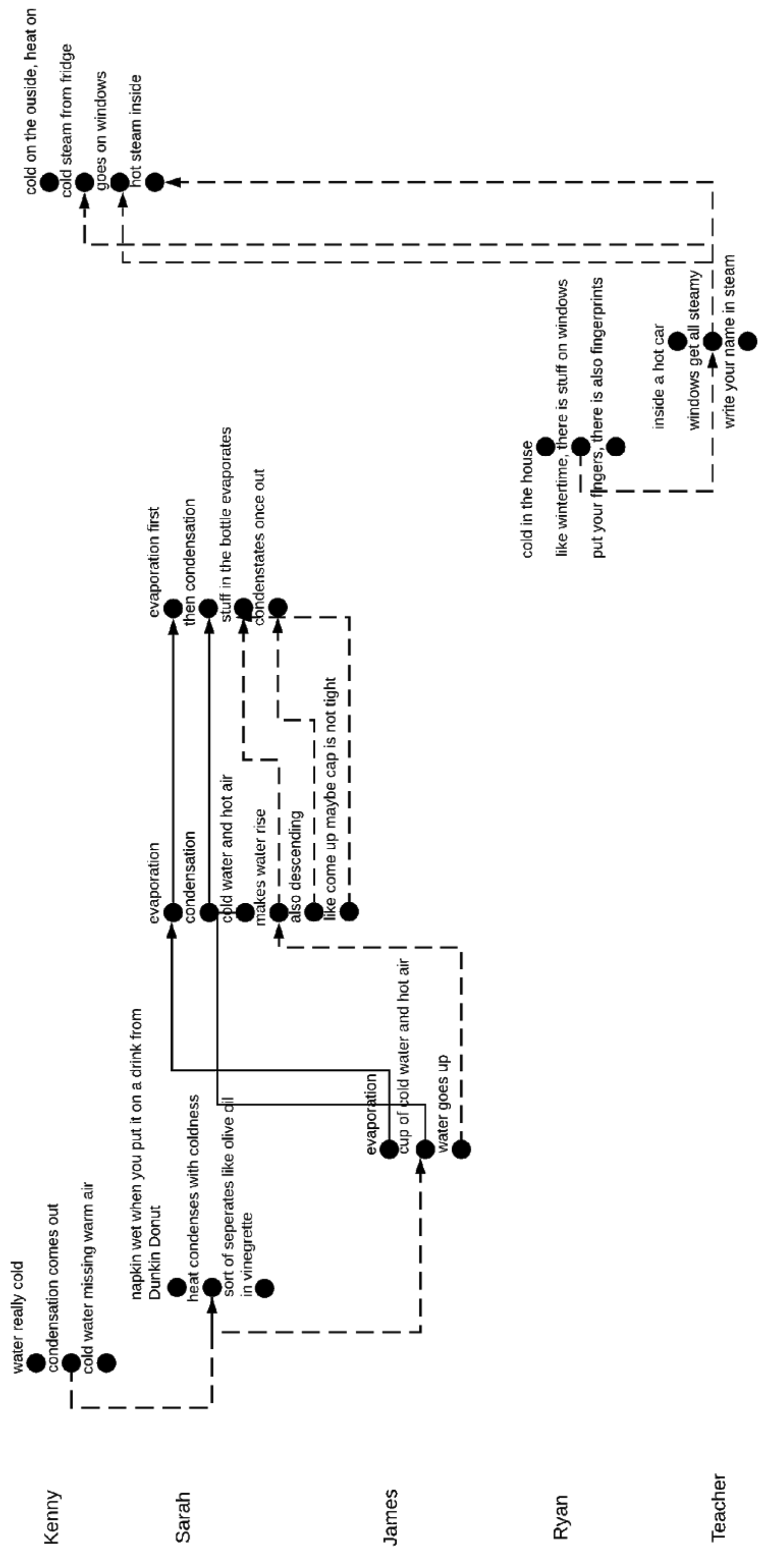

Kenny
Sarah
James
Ryan
Teacher
water really cold
condensation comes out
cold water missing warm air
napkin wet when you put it on a drink from Dunkin Donut
heat condenses with coldness
sort of seperates like olive oil in vinegrette
evaporation
cup of cold water and hot air
water goes up
evaporation
condensation
cold water and hot air
makes water rise
also descending
like come up maybe cap is not tight
evaporation first
then condensation
stuff in the bottle evaporates
condenstates once out
cold in the house
like wintertime, there is stuff on windows
put your fingers, there is also fingerprints
inside a hot car
windows get all steamy
write your name in steam
cold on the ouside, heat on
cold steam from fridge
goes on windows
hot steam inside

Figure 2: Mapping the trajectory of students' contributions around two main themes: a difference in temperature and a water cycle

Consistency and the "Water Cycle" Idea in BKF Drawing Activity: "But It Can't Be Evaporation"

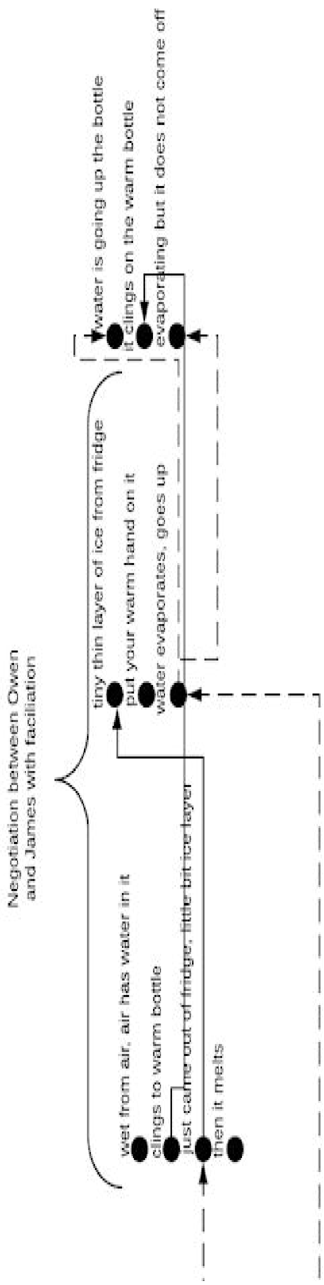
On the first day and during BKF drawing activity, there were two main contributions from James and Owen. James suggested there is water that evaporates a little and " *then it goes down the bottle.*" Owen suggested that there is a "*thin ice coating*" on the outside of the bottle that melts (Figure 3 below).

Shortly after the group started drawing, one of the facilitators joined their discussion. Owen was not convinced that evaporation could happen as suggested by James, *"That's why I don't think it's evaporation because there's like hardly any water it's all chemicals."* This response suggests that Owen assumed that the coke inside the bottle is "*all chemicals*" and not water; therefore the water on the bottle could not have resulted from evaporation. He later added, *"But it can't be evaporation it can't evaporate because that would mean it would go into the air and then you would see it stick on the ceiling.*" Consistent with his assumption about the content of bottle, Owen reasoned that if the chemical content inside the bottle evaporated, it would rise in the air and get caught on the ceiling where an observer "*would see it stick on the ceiling.*"

The contribution that there is *"water that evaporates a little"* did not match up to what Owen knew about both the content of the bottle and the process of evaporation. Evaporation translated for Owen as a process that would *"go into the air"* and therefore the water beads on the bottle could not have resulted from that process. Owen also rejected the concept that the chemicals can evaporate because it does not conform with his everyday observation of chemical-free ceilings.

James had various thoughts about the phenomenon of condensation. He asserted at the beginning of the drawing activity that *“there isn't enough heat to make the water go all the way up to the cloud so then it goes down.”* James, therefore, sustained the idea that evaporation could make the water go up a little and if there were not enough heat, then the water would go down the bottle. It is not clear what is the source of the evaporated water for James. He mentioned three possible sources: water coming up from the bottle, water from the air, and a thin layer of ice from the fridge (see Figure 3).

We can think of Consistency, in this excerpt, as a selection force that discerns ideas and contributed to pushing against the idea that water evaporates, therefore giving more explanatory appeal to the idea that there might be a thin layer of ice. It is important to note the role of the facilitator in structuring turn-taking moves that allowed members to expand and articulate their thinking as can be seen on the right-hand side of Figure 3.


Negotiation between Owen and James with faciliation
wet from air, air has water in it
clings to warm bottle
just came out of fridge, little bit ice layer
then it melts
tiny thin layer of ice from fridge
put your warm hand on it
water evaporates, goes up
water is going up the bottle
it clings on the warm bottle
evaporating but it does not come off

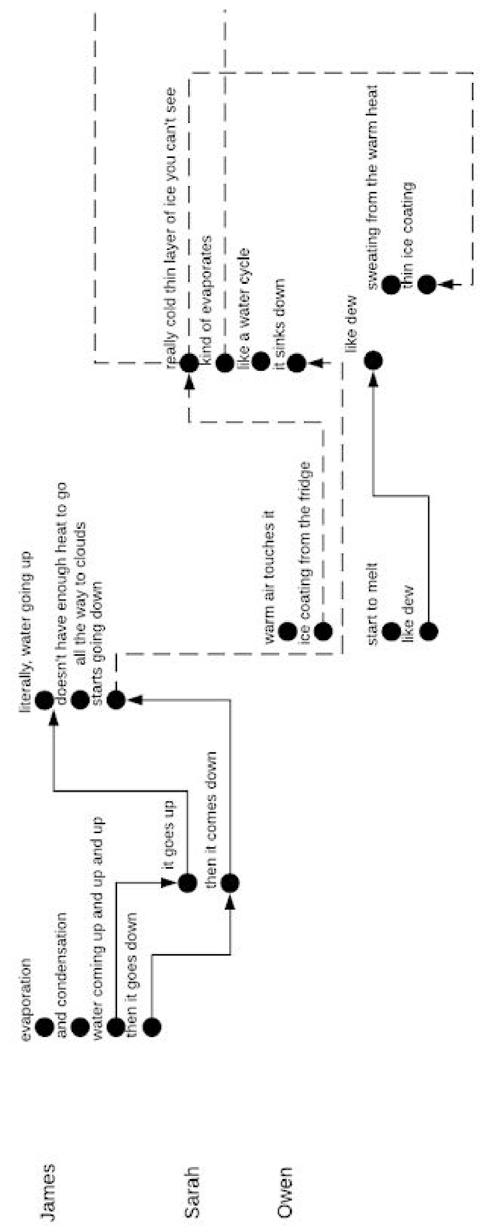


Figure 3: Mapping of the trajectory of BKF contributions around the ideas of a thin layer of ice, and water cycle during their drawing activity on the first day.

Relatedness and Generative Ambiguity in SB Drawing activity

Members of SB related the phenomenon to different observations in their drawing activity. For example, Edgar observed that the bottle is cold and dry at the beginning then later *"it starts getting all the evaporation."* He referenced a familiar experience that perhaps appeared analogous to condensation *" … uhm it was cold and it like it's just like sweating, like when the car is cold, you can it's like all foggy."* This contribution might have in turn inspired his drawing (Figure 4) that stuff inside the bottle comes out through the plastic in a process that he described as *"drying out"* perhaps similar to sweating.

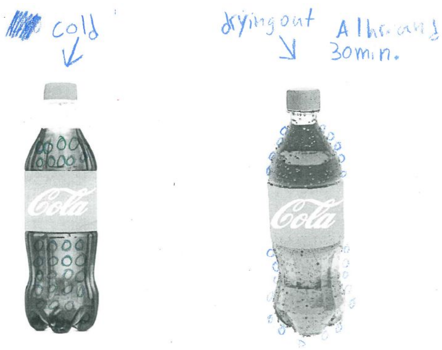


Figure 4: Edgar's drawing from the first day. The left Cola bottle is the before picture, and the Cola on the right is after one hour and thirty minutes as indicated. We see the entities inside the left bottle, are now drawn outside on the right one.

Kenny related the appearance of *"light fog"* to what happens on car windows when "*cold air mixes with the warm stuff." (see Figure 5).* Both Kenny and Edgar mentioned *"fog"* that appears on car windows, a familiar experience to them. However, Edgar related fog to *sweat* coming out of the bottle, while Kenny related fog to a difference in temperature.

We can think of these interactions as examples of two main forces acting on the contributed ideas. Relatedness operated by introducing new contributions to the selection pool. Examples include *"it's just like sweating,"* and the "*light fog"* on car windows. Generative Ambiguity also operated by allowing possible understandings of fog according to Kenny and Edgar to persist in the pool. In their animation discussion (discussed later), this agreement on fog as it relates to the phenomenon is crucial in how they came into consensus.

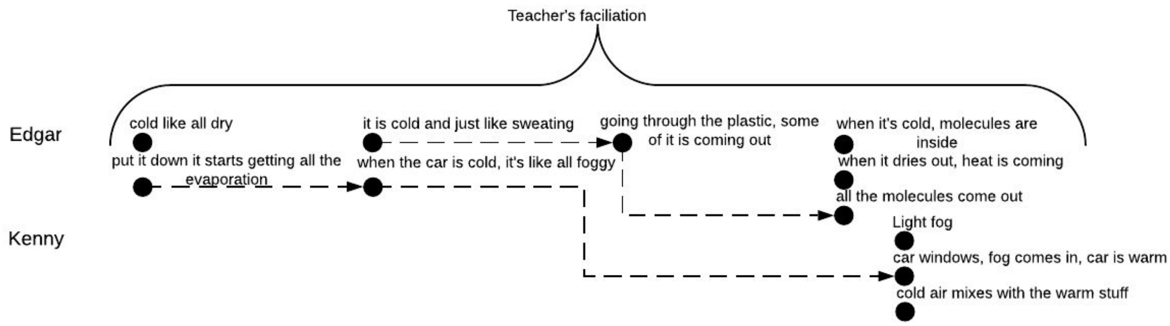


Figure 5: Mapping the trajectory of “water in the air” idea during SB drawing activity with teacher’s facilitation

Consistency, Relatedness, and Generative Ambiguity Operating on Students’ Contributions During Class Discussion

On the second day of the workshop, the students watched a video where condensation appeared on a glass filled with ice and water. The glass then turned “foggy” as students described and water droplets started forming and dripping down the glass. The teacher asked what kind of connections they made after seeing this video and how it related to their ideas on the first day. The class then worked into groups to produce a stop-motion animation to demonstrate their model on condensation.

Contributions that were consistent with the video gathered agreement among students. Both Owen and Ryan provided an explanation of how “frost” or “ice you can’t see” forms because the glass gets cold. Moreover, that ice melts and becomes the condensation we see (refer to Figure 6 below). Another student, Luis, provided a similar contribution where he suggested on the first day that evaporated water could have formed a cloud that rained on the bottle.

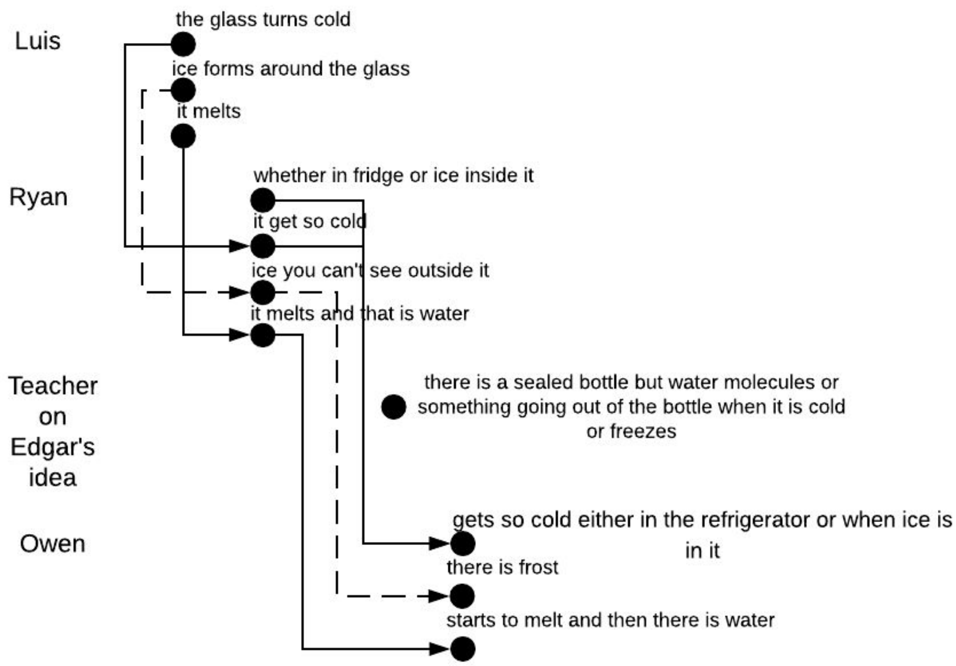


Figure 6: Students' contributions at the beginning of the second day after they have seen a video depicting how condensation forms on a cold glass

The class then turned to answer an important question "where did the [fog] come from?" (Figure 7) One student, Sheree, offered that "fog" appears on the glass because "It came from the room temperature or something." The teacher asked her to elaborate on the idea of "room temperature," Sheree suggested the place was "hot" and the ice melted with the water. The teacher asked her to clarify the relationship between the hot air and the "fog." Sheree offered that "it is cold water or something." The teacher summarized her idea as "something about the combination of hot air and cold water." The teacher's questions allowed the word "fog," which can hold many meanings, to persist while asking the student to attend to consistency between aspects of her idea.

Madison seemed to agree that a difference in temperature is what makes fog happens. She brought up a familiar situation where the car windows get foggy when it is really cold outside but warm inside the car.

The teacher, without specifying what "fog" is, related the question "where does [the fog] come from?" to students' daily experience riding in heated cars in cold weather. Some students agreed with this observation while James challenged the conditions when fog appears on car windows *"the car is not on and the heat is not on, but there is fog outside*." James provided a situation that was not consistent with Madison's contribution.

Looking at the classroom interactions and the nature of ideas, we can conceptualize three forces operating on students' contributions. Consistency to favor the "invisible ice" idea because it provided a narrative that was consistent with the ideas that water must come from somewhere and with the observation that nothing is visible (Figure 6). Relatedness and Generative Ambiguity to favor a "difference in temperature" where every day experiences of riding a car and fog appearing on windows and the generative ambiguity of the term "fog" allowed Madison's and Sheree's contributions to be considered (refer to Figure 7). However, Consistency also worked against the idea of a difference in temperature. Several students, including Kenny from SB, gestured in agreement with James (a member of BKF) when he described a situation where fog appears when there is no difference in temperature.

Edgar's contribution that water inside the bottle comes outside was not picked up by any student in the class discussion (Figure 6). In the following section, we will describe how this idea competed with other available ideas in SB group activity and how it did not get further selected and propagated.

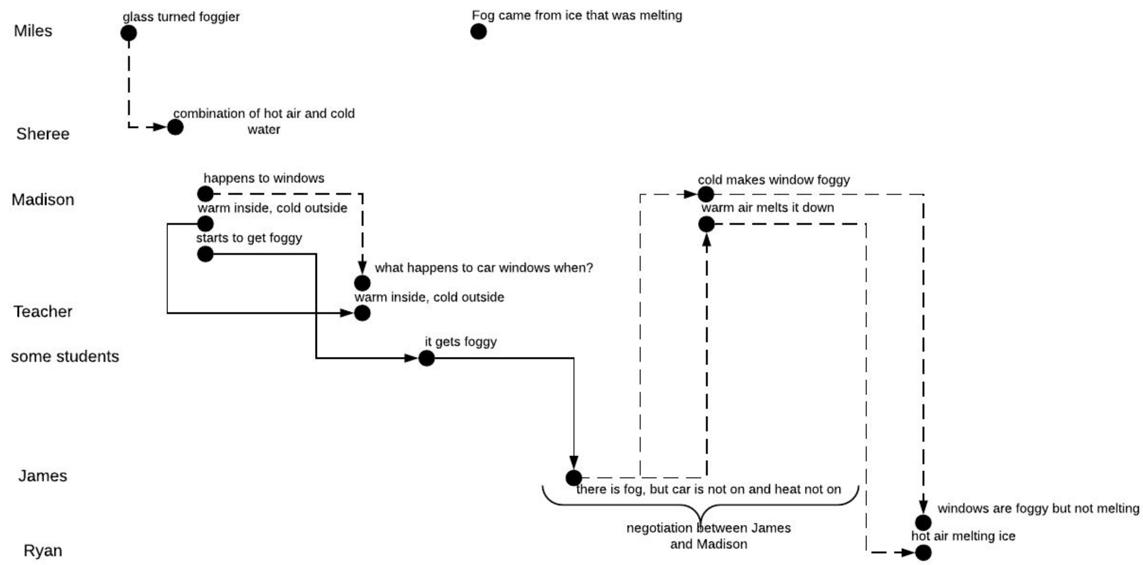


Figure 7: Second day: selection and propagation of "fog" that might have contributed to the emergence of "water in the air" idea

Selection Forces to Reach Consensus in SB Animation Activity

After the whole class discussion, each group worked to reach a consensus about what they wanted to animate. Kenny initiated the discussion in his group and related the glass getting water to the process of sweating so that *"it does not freeze up and break."* It is difficult to assess how Kenny thinks condensation happens. His ideas included "cold water missing warm air" (Figure 2) and light fog on car windows because "cold air mixes with the warm stuff" (Figure 5), but still disagreed-as evident in his gestures-with the idea of a temperature differential that Sheree and Madison presented in class.

Kenny then continued to ask Edgar what he thought. Edgar contributed that *"stuff* *inside come outside."* (Figure 8) Kenny and Edgar stated to negotiate the available ideas. Kenny quickly rejected this contribution and even made fun of it *"I strongly disagree with you because how can something that's closed and that's inside the bottle come outside the bottle?"* Kenny might have concluded that since the bottle is closed, then it is impossible for anything to come out of it. There are plenty of everyday experiences that confirm this expectation. Edgar might not have been too certain the bottle was hermetic. He later explained to the teacher that *"... it was first ice, it was just like ice. And then like, um, when it melted, all those bits came out."* (Figure 8 under teacher's facilitation) Edgar did not conclude that Coke was coming out through the bottle but instead water from the melted ice inside. The idea that water could come out of barriers might not be too foreign for Edgar. In his drawing session, he also referenced sweating *" … uhm it was cold and it like it's just like sweating, like when the car is cold, you can it's like all foggy."* What made sense to Edgar might not have made sense to Kenny, because it contradicts Kenny's assumptions and knowledge of how plastic or concrete surfaces work.

Looking at Kenny and Edgar's negotiations, we might conclude how on one hand Relatedness increased the fitness of the idea that stuff inside comes outside, however, on the other hand, Consistency pushed against it.

Moments later, the teacher joined to facilitate the discussion between the group members, asking *"where is [the water] coming from? Is it coming out of the bottle? Is it leaking through the sides? Where is it coming from?*" allowing each member to explicate their thinking and argue against one another. Kenny experienced a realization during the teacher-led conversation where he said *"since you [the teacher] said something about that, I thought that cuz you know how, there's, how there's like water everywhere from evaporation? I thought that that comes one that, on that on the glass."* Kenny presented a new contribution that the water on the glass comes from the evaporation all around us. The teacher addressed the rest of the group to discuss what they think about it.

Edgar	I think um, I can agree with that because um, that's kinda similar with mine. Not really, but I see one thing that's similar that like um, like, it's cold. It's just like it's just like the temperature is cold, so the room temperature is like warm. And then like, um when the cold and warm mix together they like make fog or something like that.
Teacher	Okay, so there's something, you're thinking there's something about that heat and cold part. So, are you changing your idea a little bit about it leaking out of, or like, somehow going through the bottle?
Edgar	Yeah
Teacher	So, if it's not coming through the bottle, where is this water coming from?
Edgar	The fog
Kenny	The air
Teacher	so the air, when you say fog you mean like
Edgar	Fog, air
Teacher	Okay, you mean like the air around it?
Edgar	Yeah, the air.

After Kenny presented the idea that water in air from evaporation comes onto the glass, Edgar switched his thinking about the source of water from one that is coming from inside to coming from the outside. However, he maintained that the cold temperature and the warm room mixed to form the fog. The teacher then asked where the water came from, and Edgar replied "fog, air." For Edgar, fog as a term is the source of water and at the same time perhaps the air around the bottle, probably as the medium where this mixing is happening. Listening to Edgar's new contribution about the fog, Kenny replied *" I disagree and agree because I agree about the fog part because maybe the evaporation around it make, um, makes the fog. And, yeah."* Edgar and Kenny now agreed that they wanted to show fog coming onto the bottle from the outside. Miles, the third member of the group, played an important role in questioning his peers' and his assumptions about the phenomena, driving the conversation at times about where the fog comes from. Nevertheless, he had difficulty articulating an alternative contribution to the ones provided. The teacher privately talked to Miles and explained Kenny and Edgar's animation idea and asked him to help his team members accomplish their goals.

Generative Ambiguity realized by the malleable quality of fog played a role in relating in two different ways to the phenomenon. For instance, the idea of "the cold and warm mix together" to form fog presented by Edgar was not taken up by Kenny. Instead, the appearance of fog came from evaporation all around us. Nevertheless, Edgar now subscribed to the idea that fog or the air around the bottle makes the condensation. In addition, Authority realized in the teacher's social position in weighing on which idea to pursue perhaps discouraged Miles to add to the selection pool and contributed to the group reaching consensus.

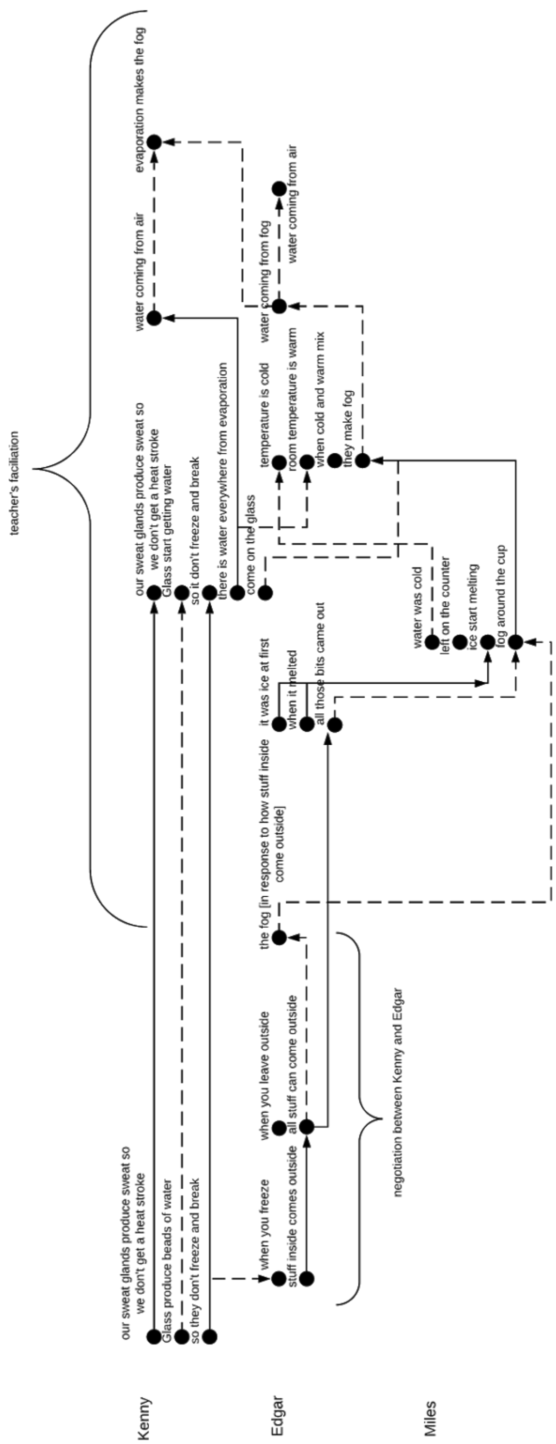


Figure 8: Mapping of the trajectory of *water in the air* during SB animation activity on the second day.

Selection Forces to Reach Consensus in BKF Simulation Group Activity

On the third day of the workshop, Sarah called for the teacher to help the group decide which idea to simulate. Sarah and James agreed that water vapor hits the bottle- a contribution she provided at the beginning of the class discussion.

1	Teacher	so tell me what you mean by water vapor. Just so I make sure I understand what you are talking about.
2	Sarah	Like (short pause)
3	James	water in the air
4	Teacher	water in the air so is there, like the water that we drink?
5	Sarah	no, we can't see it. no
6	Teacher	so what is it? What is water vapor?
7	Sarah	it’s more like fog. I don't know
8	James	yeah, fog
9	Teacher	okay So more like fog, but fog that we can't see?
10	Sarah	well, it's like. It’s, you do know what we're trying to say
11	James	like fog that we can't see

James and Sarah worked together with the teacher to bridge their proposition that *water vapor hits the bottle* with the term fog. Fog here holds multiple meanings in relation to water vapor; Sarah suggested that water vapor is closer to fog than the water we drink (lines 4 and 7). James related water vapor to a fog that we cannot see (line 11) perhaps as opposed to the fog the students saw forming in a video presented on the second day depicting a glass filled with water and ice forming condensation, or the fog they discussed following the video that forms on car windows when the heat is on, and the weather is cold. It is not clear how Sarah came up with the water vapor idea, James who agreed with this contribution suggested on the first day that condensation occurs when water evaporates but could not go all the way up to the clouds because *"there isn't enough heat"* so it goes down and clings to the bottle (Figure 8). During the drawing session, one of the facilitators asked about the source of this evaporated water and after a few turns James contributed that *" the air has water in it no matter, but we can't feel it."* In the above excerpt, James related the term water vapor to water in the air, then related water vapor to fog that we cannot see. The term "fog" moved to the forefront of the class conversation on the second day after the students watched the video (reference Figure 6).

Generative Ambiguity of "fog" facilitated the convergence of Sarah and James' contributions to the idea that "water vapor is fog we cannot see." In addition, we could also argue that the term "water vapor" also could have held multiple meanings. Sarah contributed during the class discussion on the third day that water vapor in the air hits the bottle and then it drips down because air is filled with *"oxygen and water vapor."* Therefore, she perhaps conceptualized water vapor as a stand-alone substance in the air which could be different from James' understanding of water vapor as air that has water we cannot see.

Owen continued to argue against that model and suggested the water came from the melting of a thin layer of ice around the bottle. The teacher who facilitated these discussions made the following suggestion to move the group's work forward.

Teacher So Owen, for now, what we're gonna say is, just based off simple majority, there's two here saying one idea and there's one saying a different idea. I respect both, but because there's two of you, I want to start with trying to simulate the idea that Sarah and James are talking about. Okay? That doesn't mean Owen that when you go over simulations and we look at different people's ideas, that you can't, you can't still say I still think it's this way. You can argue against your own simulation.

The group needed to come to a consensus on which idea to simulate. Owen, until that point, was not convinced that water vapor inside the house sticks on the bottle. He reasoned that if that was true then *"that would mean you drench everything inside."* Consistency here is pushing against the idea of "water vapor".

At this point, the teacher who had structured the conversation around clarifying each member's contribution realized that due to time constraints the group must select one idea to model. As a result, he reverted to the democratic process of eliciting the votes and selecting the majority. Authority translated as the underlying structure of decision making and who is allowed to make them had the final say in selecting the water vapor idea over the invisible layer of ice (see Figure 8).

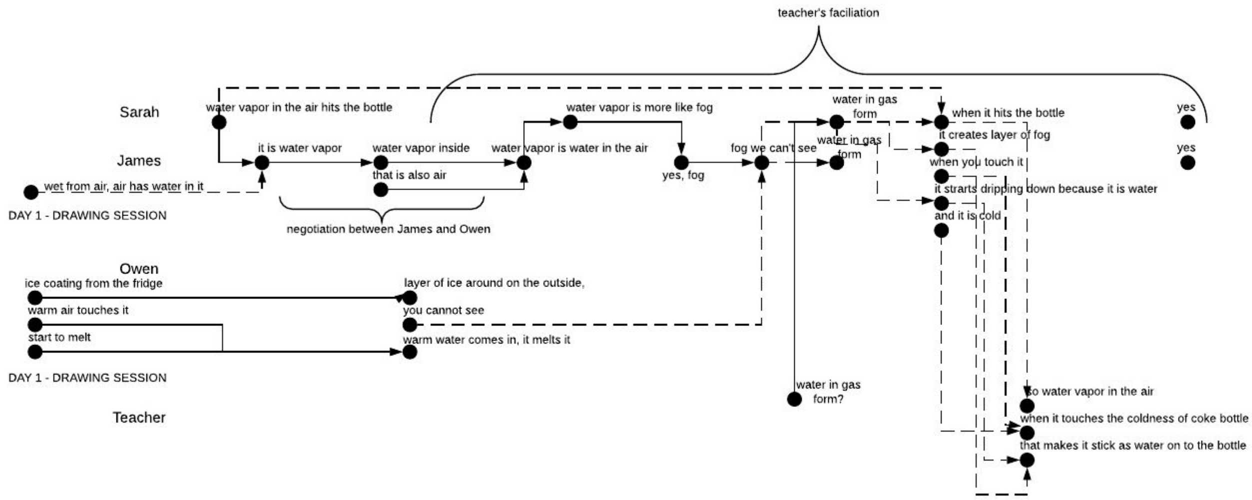


Figure 8: The selection and propagation of contributions to reach consensus between Sarah and James on the “water vapor” idea

Selection Forces to Reach a Consensus that “The Fog is the Water Vapor in the Air”

On the final day of the activities, SB and BKF among other groups presented in front of their classmates. SB was the first group to showcase their simulation. Kenny presented that evaporation that happens all around us comes onto the bottle and makes the condensation. BKF was the last group to present and Owen explained his group’s simulation, *“bottle is collecting the water droplets”* and then added on his own accord *“that's like the evaporation basically,”* and James agreed. Owen provided a new contribution that evaporation is the source of the water droplets in their simulation. It is likely that Owen reasoned about the similarities between the idea of *water vapor* with the process of evaporation as demonstrated in SB presented simulation. Miles, a member of SB asked about the fog, *“where would the fog come in?”*

Owen Just like yours//

James //The fog is the water vapor in the air, so when it is hitting the water bottle it is turning into like a fog, and then the fog gets warm, so it starts drop down the water bottle

Owen and James realized the shared mechanism between SB simulation and theirs. The two groups simulated water droplets coming onto the bottle. SB attributed the source of water to evaporation while BKF agreed that it came from water vapor in the air. James also began to explain how water vapor turned into water beads dripping down the water bottle. He offered a new contribution that water vapor turns to fog when it hits the bottle and then that fog gets warm and drop down. This verbalization is similar to what SB discussed in their group *"I agree about the fog part because maybe the evaporation around it make, um, makes the fog."*

The ambiguity of the term fog played a role in giving more lifetime to contributions with different mechanisms on where fog came from. The knowledge-building discussion around the presented simulations in class allowed James and Owen to clarify and connect the various terms to describe the mechanism. Looking at the interaction of ideas, we can argue that Generative Ambiguity and Consistency operated to reach a consensus that "fog is the water vapor."

Reaching consensus between BKF and SB followed complex and different trajectory paths and timescales, both on the individual and the group level. Moreover, we cannot say that all members at that point subscribed to the described mechanism. What we could claim is that from a memetic perspective following the lifeline of students' contributions and paying attention to the interaction of ideas, there are interactional forces that worked continuously to select, propagate and refine contributions that eventually made to sense to students.

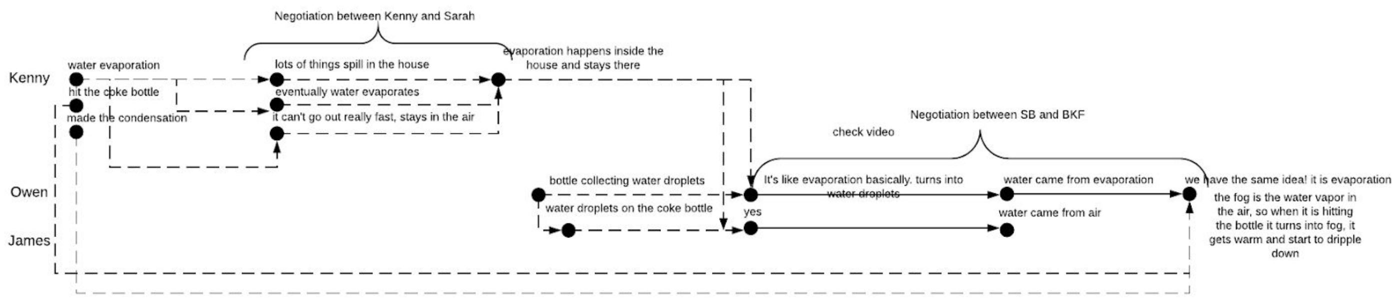


Figure 9: Mapping of SB and BKF contributions to reach consensus that “fog is the water vapor” while negotiating their simulations

Summary of the Selection Forces

We identified four selection forces after repeated viewing of the data and paying attention to students’ argumentation and discourses around modeling. Below is a summary of each force and how they operated in our data.

Relatedness

Definition: The property of how similar an idea is with one’s personal experiences, either phenomenologically, semantically, or through other mechanisms of relating one phenomenon to some other phenomenon or observation.

Relatedness operated noticeably on the first day of the workshop. Many of students’ contributions of “where the water came from” referenced other phenomena which the students identified as similar. For example, Ryan mentioned fingerprints touching a soda to introduce his idea that there is stuff on the bottle we cannot see (Figure 1). There was no shortage of experiences the students shared and agreed upon during whole class discussions. People are always making sense of whatever they encounter: the sense they are making is not always about science, but is it grounded in how they can relate their understanding of the offered explanation to what they know.

In our data, Relatedness operated by introducing ideas to the selection pool and selecting for ideas that relate to students experiences. For example, Sheree picked up the fingerprints example that was mentioned by Ryan (Figure 1). Relatedness also occurred during student groups' discussion to give more credibility to their contributions.

Consistency

Definition: how an idea aligns with other expectations or observations.

Consistency is a force that discerns contributions and selects the ones that sit well with the participant's assumptions and observations about how the world works, and it also operates by pushing against contributions that violate these assumptions. Consistency frequently occurred when students were reasoning about the mechanism of the phenomenon when they negotiated multiple possible contributions. Ideas that confirm expectations or observations that align with how the participant thinks the phenomenon works mechanistically have a higher fitness measure than the ones that violate expectations or observations about consistency and coherence. That is to say that the contextual knowledge that a participant thinks is relevant to how a phenomenon mechanistically works.

Generative Ambiguity

Definition: The property of how a contribution or a term can hold multiple meanings that allow participants to advance the conversation, further develop their ideas, and refine *their models around the phenomenon.*

Generative Ambiguity worked by allowing potentially different ideas to coexist. It operated by advancing certain contributions. For example, on the second day, the students mentioned “fog” in their contributions. One student, Miles referred to “fog” that came from ice melting in a glass, while Madison referred to differences in temperature that made the “fog. ” The students might have had different understandings of “fog” but those differences did not surface. The ambiguity of the term allowed it to persist without scrutiny.

Authority

Definition: The social positioning of the contributor to other participants, and the property of discursive moves that adds credibility to particular ideas.

Authority as a selection force also governs things like the time devoted to discussing a particular contribution, or the forms of justification used for some ideas over others. Although the teacher structured the modeling activities to support students’ thinking, he and other facilitators were still regarded as knowledge authorities who know the right answer. Sarah on more than one occasion questioned the facilitators which idea is “true” and on the third day whispered to Owen who wanted to work on his idea *“Well, what do you think... trust me it's my idea I'm positive. [getting closer to Owen and whispering] I... I asked Mr [name of the teacher] [indistinguishable] and he said: "Yeah it's right.*"

Authority is a complex force that extends to the social positioning of students. SB group members held Kenny in a favorable light. They referenced him as “smart”, included him in every move during the activities, and Edgar was even uncomfortable when he had to argue against Kenny's thinking. Kenny also demonstrated a leadership role in his group. On different occasions, he encouraged his group to focus on the task at hand, argued against contributions that did not make sense to him, and additionally talked on behalf of the group more times than often *"We all agreed on that idea."*

Authority is a selection force that has multiple levels of enactment. It operates by preferencing one idea over the other depending on the social positioning of the contributor. In our data, Authority operated since the first day and mostly with other forces in the structured class activities that allowed students to engage with the facilitators and their peers about their thinking.

Discussion

The Idea Fitness Framework implies a beginning set of selection forces that can be used for a more systematic study of the dynamics of idea propagation in a classroom. The perspective of ideas advances our understanding of classroom dynamics by conceptually flipping students' agency. The core of memetics, as it applies to our study, is to remove the association between students and their ideas. In its place, all available ideas are treated as agents that could work for any student, and therefore their flow and propagation are depended on their perceived epistemic usefulness in the dynamic system under study. Our analysis revealed that students as members of a knowledge community not only introduced ideas into the selection pool but were continuously assessing all the available ideas whether it came from their peers, teachers, or their own experiences, knowledge, and observations. However, the shape of those ideas was in constant flux. Indeed following the trajectory of contributions, it appeared that they are in a shuffling mode which informs us as researchers and educators that students' are continually shifting their thinking in interaction with those ideas to seek mechanism or relatedness between ideas and their observations. Students also provided counterexamples to challenge their peers when the contributions did not adhere to consistency or related to their observations. These practices seemed to emerge without explicit instruction when students assessed, communicated, and negotiated ideas. Nevertheless, the analysis illuminated other forces that are also at play that affected these emerging practices. Authority could be regarded as restrictive force selecting particular contributions. Students' awareness of a "correct" answer and their regard to their teacher as someone who possesses it perhaps shifted some of their attention to what the teacher thinks instead of assessing ideas. However, our data also show that Authority is not enough alone to reach consensus. Owen, who had doubts about the idea of water vapor, eventually argued for this model in conversation with members from other groups.

There is one but an urgent matter that calls for attention; the facilitation and the structured class activities influenced the evolution of and the students' interactions with ideas. Our data is replete with instances where constant negotiation about the meaning of "fog" or clarifying the source of water, for example, introduced new ideas to the selection pool as well as refined those contributions to have a higher fitness measure. For example, the teacher asked if water vapor is "water in a gas form" and both Sarah and James picked up this contribution (Figure 8 under teacher's facilitation). Facilitation allowed students not only to share but reflect on their thinking and directed the conversation to focus on the particulars of each contribution when it was productive to do so. At other times, Generative Ambiguity and the teacher's moves not to specify the meaning of fog, for example, allowed ideas to coexist, evolve, and propagate. Therefore, it raises considerations for design-based research where educators, tools, and spaces to build a community of learners must account for the ways students engage in productive discourses.

Previous research investigated how a community of learners establish meaning and build practices together with their teacher. For example, Yackel and Cobb (1996) examined students' mathematical beliefs and the formation of sociomathematical norms, "normative understandings of what counts as mathematically different, mathematically sophisticated, mathematically efficient, and mathematically elegant in a classroom." (p. 461) They presented evidence that "reflexivity" of the interactions between the students and the teacher establish taken-as-shared meanings of mathematical beliefs and norms (Yackel & Cobb, 1996, p. 470). The IFF complements this line of research by investigating the affordances of the ideas along their evolution to answer the question of why certain ideas persist and propagate and others fade away. However, the role of teacher's facilitative moves that produce this *reflexivity* warrants further investigation.

Further research is also needed to expand this framework to additional knowledge communities asking different science questions. We are curious to know how each of these identified forces functions and operates with different students grappling with different technological tools. The framework brings forth an old but persistent conclusion that learning in a community is enriched by having multiple views (Rosebery, Ogonowski, DiSchino, & Warren, 2010) where learners can work together to think and discern these contributions according to their assumptions and experiences. Enacting Knowledge Building principles to shift the students from learners to contributors in a knowledge building community ensures that no one force dominates; instead, they work together to favor the contributions that are relevant and make the most sense to participants.

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