Developing Mechanistic Model-Based Explanations of Phenomena: Case Studies of Two Fifth Grade Students' Epistemologies in Practice over Time

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Abstract: To foster meaningful engagement in scientific practices within classrooms, we must better understand how students can productively develop their epistemologies in practice (EIP) across contexts. This study traces how two high-performing fifth grade students engaged in scientific modeling across three modeling-centered units over one and a half years. To analyze their epistemologies in practice over time, we examined their model-based explanations and reflective talk about the rationale and purposes of their explanations. While both students developed more mechanistic explanations of phenomena, they did so in different ways. One developed a meta-level rhetorical strategy to explain "how and why" phenomena occurred, even in non-prompted contexts. The other used a reductionist analytical strategy to look for deeper level mechanisms of phenomena. These cases provide evidence that students develop EIPs across contexts, and leads to insights about what develops, what might influence this development, and how EIPs can be further supported in classrooms.

Supporting Meaningful Engagement in Scientific Practices

The science education community has taken a "practice turn" with respect to K-12 reform efforts (Ford & Forman, 2006). The Framework (National Research Council, 2012) and NGSS (National Research Council, 2013) have highlighted the idea that students should learn core disciplinary knowledge while engaged in scientific practices. This turn recognizes the importance of engaging students in communities of practice (e.g., Wenger, 1998) that pursue classroom versions of the knowledge-building goals embraced by the scientific community (e.g., establishing claims supported by empirical evidence, and generating, evaluating, and revising knowledge products that embody descriptions and mechanisms of phenomena). But for these goals and related practices to be meaningful (rather than procedural), they must be guided by the *epistemological considerations* that characterize disciplinary science (e.g., Duschl, 2008). However, engaging students in epistemologically meaningful practices in K-12 classrooms is extremely challenging. Furthermore, the science education and learning sciences communities do not yet have strong understandings of how students develop their epistemologies in practice over time (across units and classroom settings) and what increasingly productive epistemic engagement might look like. Epistemological considerations are critical for engaging in scientific practices in ways that are meaningful for students and authentic to the discipline. If we are to successfully enact reform efforts emphasizing student engagement in scientific practices, then we must better understand how students learn to use epistemological considerations to productively engage in practices over time.

Studying Students' Developing Epistemologies in Practice

Our work has centered on how students learn to engage in scientific practices within elementary and middle school contexts (Schwarz et al., 2009). In particular, we have been studying how elementary and middle school students engage in scientific modeling, explanation, and argumentation practices to make sense of the world and the role of epistemological considerations in making those practices meaningful. By epistemological considerations, we refer to students' practical epistemologies as they are engaged in practices – or notions about the knowledge-related purposes, methods, and goals of the work in which they are engaged (Sandoval, 2005). We argue that students need to understand and use epistemological considerations for productive and meaningful engagement in scientific practices. For example, developing and revising models that address the mechanism of phenomena lies at the core of the scientific endeavor; thus, considering the degree to which an explanation is mechanistic should guide learners engaged in scientific practice. We termed these epistemological considerations that frame and guide practices "epistemologies in practice" (EIP) (Berland, Schwarz, Kenyon, & Reiser, 2013).

Our prior work has found that students can attend to and productively engage in several epistemological considerations. One such consideration includes students' justification of their knowledge product (such as a model-based explanation) and ranges from students basing their decisions on authoritative claims to basing their decisions on empirical evidence and theory; in short, we label this as the evidence consideration. Another consideration includes students' decisions concerning what kind of answer the knowledge product should provide, and ranges from students providing visible descriptions of phenomena to providing non-visible causal mechanisms and explanatory processes that explain or predict phenomena; in short, we label this as the mechanism consideration. These, as well as our other considerations, emerged from prior empirical and theoretical work (Schwarz et al., 2012) and share similarities with epistemic criteria in other science education research (Duschl, 2008; Pluta, Chinn, & Duncan, 2011).

Our overall research goal has been to investigate how to support meaningful scientific practices by developing students' EIPs within scientific practices. We aim to determine how and why students' EIP develop or shift over time and to investigate promising pathways for EIP development in scientific practices. Therefore, our research question asks: *How do students' EIPs develop or shift over time and across contexts with respect to the kind of model-based explanations they generate about phenomena?* To address this question, we analyzed data from two high-performing fifth grade students across several science units. We target the analysis around the kind of model-based explanations students generated particularly with respect to whether or how they attended to mechanism, an aspect that played an important role for both students. Mechanism, or causal explanatory processes, are critical in science and for model development and use (Braaten & Windschitl, 2011; Russ, Scherr, Hammer, & Mikeska, 2008). We also analyzed students' reflective talk about their work to examine their notions of what is important in a model-based explanation and how that may have impacted or framed their engagement in the practice.

Method

To determine how students' epistemologies in practice developed or shifted, we interviewed a cohort of ten fifth grade students from four classrooms in 2011-2012 and a second cohort of fifteen fifth grade students from four classrooms in 2012-2013 as they participated in several model-based science units over time. These units engaged students in iteratively developing and revising scientific models that addressed how and why the phenomena of evaporation, condensation, and light occur. All students attended a suburban public elementary school in the Midwest. In this paper, we describe our analysis of data from one student in the 2011-2012 cohort (LS) and one student from the 2012-2013 cohort (JS) who shared the same fifth grade teacher in subsequent years. Both were academically high-performing female students of European-American ethnicity and were chosen for this analysis because they were highly reflective and articulate ten-year-olds. We also chose these students because they made some relatively clear and significant shifts in their EIPs over time, which was often not as visible in other fifth grade students' data. To determine how their EIPs developed over time, we interviewed LS three times (post-evaporation, post-condensation, post-light) in the 2011-2012 school year and three times (pre-chemistry, mid-chemistry, post-chemistry) in the 2012-2013 school year; we interviewed JS four times (pre-evaporation, post-condensation, pre-light, post-light) in the 2012-2013 year.

During the semi-structured interviews, we asked students to describe their (1) models and model-based explanations generated in class, (2) rationales for developing and revising those models, (3) development and application of models and model-based explanations in new contexts, and (4) reflection on this process. For instance, during the condensation interview we asked questions such as: "What did you want your final condensation model to show?" "How does your model answer the question 'How and why do liquids sometimes appear on cold surfaces over time?'" "Looking back at your initial condensation model, what were some important changes that you made and why?" and "Can you use your revised condensation model to explain the phenomenon of how and why rain forms?" As such, the interview elicited information about students' reflections on their model-based explanations and the process of modeling in class, as well as their own practices developing and using model-based explanations.

Table 1 shows the coding rubric for the mechanism EIP consideration we used to code the students' interview responses. The mechanism coding rubric was developed from our prior work (Schwarz et al., 2012) and addresses the kind of answer the knowledge product (i.e., model-based explanation) provides. Similar to Braaten and Windschitl's (2011) framework of ambitious practice for explanation, we coded students' model-based explanations as ranging from students attending to non-mechanistic details (Level 1), to descriptive accounts (Level 2), to mechanistic explanatory processes (Level 3). Descriptive accounts (Level 2) only address *how* a phenomenon happens, which can be a chronological order of events or the condition(s) under which a phenomenon occurs. In contrast, explanatory processes (Level 3) include a causal relationship or mechanism that also addresses *why* a phenomenon happens. These ordered levels do not necessarily imply a sequential or developmental pathway. Instead, they are meant to capture increasing levels of sophistication with respect to the type of explanation students generate.

It is important to note that we did not code the students' responses based on one or two utterances in the interviews. Rather, we analyzed student talk, as well as their diagrammatic model, throughout the interview. For example, if a student provided a partial explanation of the phenomenon in one response and another partial explanation in another response later during the interview, we combined those responses to determine if s/he produced a full mechanism-based explanatory process. By analyzing the students' interview responses and models holistically, we more accurately characterized their model-based explanations about phenomena.

Table 1: Scoring rubric for the type of model-based explanation.

Level	Students' model-based explanation of the phenomena attends to:
3	a partial or full mechanism-based explanatory process that addresses "why it is happening"
2	a partial or full descriptive accounts (including sequences) that addresses "how it is happening" without a mechanism-based explanatory process
1	details that only focus on visible aspects of the phenomenon

Note: If explanations were scored slightly above/below the identified levels, a positive (+) or negative (–) or sign was added (e.g., 2+, 3–).

In addition to using the scoring rubrics to code students' model-based explanations, we also coded the reflective talk that accompanied their decisions and justifications. Students' reflective talk often reveals their views about the purpose of models/modeling or their notions of what is important in a model or explanation, which is critical to better understanding the epistemologies students leverage within their practice. As such, we analyzed LS's and JS's reflective talk to determine why they attended to particular aspects of their model-based explanations. Our analysis of this talk used an inductive approach informed by grounded theory methodology (Charmaz, 2006) to determine reoccurring themes and approaches students brought to justifying their decisions about their model-based explanations. The authors of this manuscript compared and contrasted their individual analysis of students' themes and approaches to decide what themes best fit the patterns in the evidence. While refining our analysis of students' reflective talk, we found that students had particular approaches and ways of framing what was important to include in a model-based explanation. These themes or approaches aligned with several of Braaten and Windschitl's explanation categories (2011), including views about the purpose of an explanation as a simple causal story or as a justification for a claim or argument.

Prior Results and EIP Analysis for Two Cases

Our prior analysis of interview and written data from the larger sample of fifteen focus students indicated that on average, students made modest improvements in their overall EIPs throughout the year and across curricular contexts. In particular, we found productive shifts with respect to all EIP considerations across the evaporation and condensation unit and a smaller shift to the end of the subsequent light unit. Our prior analysis also suggested that the nature of instruction and students' attending to particular EIP considerations impacted how their EIPs developed over time (Schwarz, et al., 2013). Additional analysis of students' embedded assessments from a larger sample of 113 students in a separate study indicated that they significantly improved their attention to mechanism from the evaporation unit to the condensation unit, and modestly improved their attention to mechanism from the condensation unit to the light unit.

In ongoing work to determine how and why such changes might have occurred, we then analyzed the written and interview data from a range of students in greater depth. Our analysis indicated that some students foregrounded heuristics or strategies which seemed to function as lenses, or potential scaffolds, in using their EIP in future contexts. In this study, we report on how two students, LS and JS, did so in particular and non-identical ways. We illustrate their shifts as well as their heuristics or strategies through excerpts of their interview transcripts and diagrammatic models over time. Such data are challenging to present concisely because they span across time and are embodied in particular contexts with specific meanings. Nonetheless, we show how this evidence illustrates visible patterns that contribute to our understanding of how LS and JS developed their EIPs over time with respect to the kind of model-based explanations they generated.

Case 1: LS – Making Models That Explain How and Why

LS was a student from the 2011-2012 fifth grade cohort whom we followed into sixth grade in 2012-2013. In October 2011, we interviewed LS mid-way through the evaporation and condensation unit. We asked LS about the changes she made between her first and second diagrammatic models of evaporation. When asked what she was trying to figure out with her [revised] model (Figure 1), she responded that she was "trying to figure out evaporation and how much time it takes to evaporate." In this instance, LS talked about how long it took for evaporation to occur as a descriptive, rather than mechanistic (i.e., causal), account. When asked if she could talk about the changes she made between the two models, she stated, "I didn't have any temperatures or how and why's [in my first model], so I decided to do how and why [in my revised model]…" While it appears from this reflection that LS may be attending to more causal aspects of the phenomena ('why') in the revised model, she referred to the 'why' in a descriptive manner, indicating that her revisions came from knowing "what actually happens from doing experiments" and ideas from the simulations. When asked how the written descriptions in her revised model improved her model and the reasons she included them, LS responded that "it gives more of an explanation about what happens and more evidence of what I did." At this point, LS's ideas about her model were primarily focused on capturing what happened from the experiments and the computer simulation in support of her model, rather than capturing how or why they occurred.

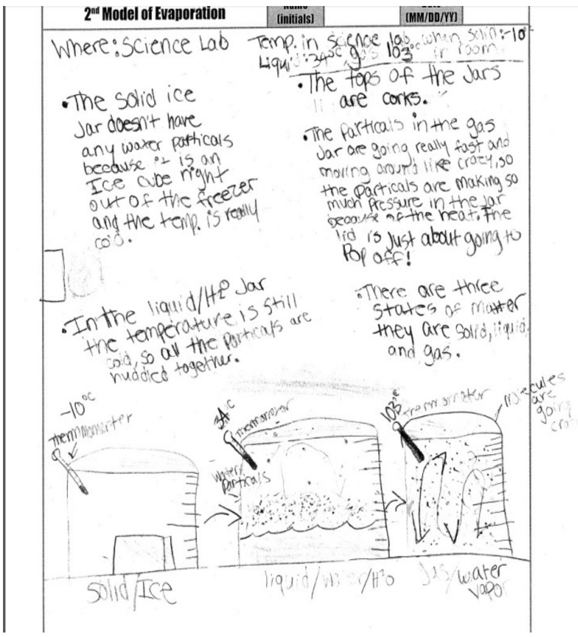

Figure 1. LS's Revised Model of Evaporation

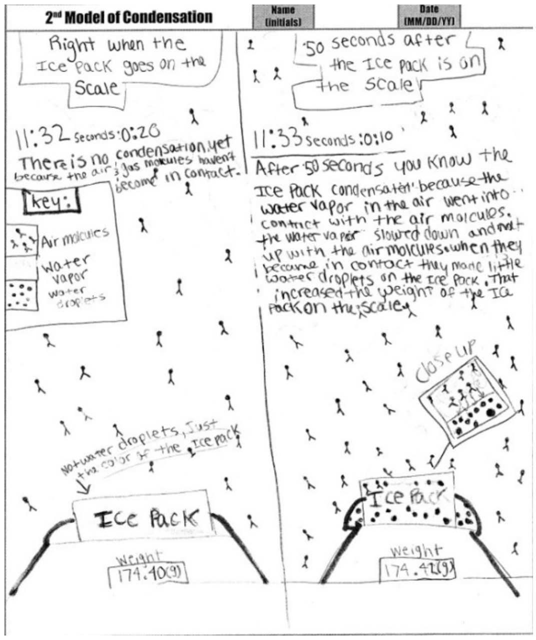

Figure 2. LS's Revised Model of Condensation

Analysis of LS's revised model of evaporation (Figure 1) supports this interpretation and indicates that she focused on the states of matter (something often emphasized in school) rather than the process of evaporation. Although her model was predominantly descriptive (using temperature, etc.), she included details at the molecular level about particles. LS appeared to be documenting information about evaporation without necessarily attending to how or why evaporation was occurring. As such, her model-based explanation and justification was scored at a Level 2 because it provides a descriptive account (sequence of steps) that addresses "how evaporation is happening" without providing a mechanism-based explanatory process (such as water particles spreading out into the air when liquid water comes into contact with air).

When LS was interviewed at the end of the condensation unit in December 2011, the nature of her talk and model showed an increased level of sophistication and orientation towards mechanism, including her notions about model-based explanations (see Figure 2). When asked if she could explain how and why condensation happened in the written question, LS said it was because "the air molecules get cold. … [and the] water molecules [are] coming into contact with the air molecules and making little droplets on the ice pack." This statement, along with her model (in which she wrote "…water vapor in the air went into contact with air molecules. The water vapor slowed down…") and reflective talk, indicated that she provided a partial mechanism for how condensation happens (water vapor comes in contact with cold air, and water vapor slowed down to become water droplets). Her reflective talk showed an increasing emphasis in addressing "how and why" questions to explain her model. For example, when LS was asked what she was trying to figure out with the models she created, her response was that she wanted to know "How and why condensation and evaporation happens." Similarly, when asked if she could talk about the changes she made between the two models, she pointed out that she "…didn't add how and why in this [initial model]…" Her sense of mechanism also became somewhat more sophisticated when she included invisible particles to convince people how the phenomenon happens. When asked which activity addressed this change, LS responded that "…the experiments and probably from the simulations, too, how molecules move and at what temperature and what pace and stuff." Nonetheless, when asked what her group thought was important in a model, she said that they needed "…to have a key and an explanation and evidence and to have people be convinced about what we were doing." At this point in the year, we see that LS is still focused on "what's happening" because she included the actual experiment into her models. At the same time, she also started to recognize the importance of "how and why" when shifting from "what's happening" to "how's it happening" at the molecular level. This resulted in our scoring LS as a low Level 3 for this EIP consideration.

In April 2012, LS finished a short modeling-based unit on the nature of light and was interviewed about her understanding of light and her modeling experiences. Within that post-interview, we again saw that her performance and ideas about mechanism and notions of explanation developed further. For example, when asked, "Could you please describe your final model?" She replied:

"…So right here, the light source is coming to the person's eyes and also the light source is coming to the cup and the image of the cup is traveling and reflecting to the eye. So I also did reflecting and it says how you see the cup…. It says that the cup is shiny and smooth so [the light] reflects off of it and bounces off. And I said that the light source travels to the cup and an image of the cup travels to the person's eye so that she can see. For scattering, the light bounces off the hard, rough wood table and the light travels and bounces in different directions, making light shine everywhere in the room. … We see things because there's a light pathway …. Scattering happens because the surface is rough, unlike reflection where the surface has to be smooth."

This excerpt illustrates that LS is capable of identifying the reason why people see the cup. For instance, she said that she can see the cup because the light pathway travels from the light source to the cup, which is then reflected to her eyes; this is as an explanatory process. This response is different from a typical fifth grade descriptive account in which a student might say that we could see the cup because of the light, or because the person faces the object. In this excerpt, LS also explained the difference between reflection and scattering by using the same explanatory process, a light pathway, and further discussing how non-visible light moves by bouncing off in different directions. LS describes a fully-mechanistic explanatory process, which is why we scored her response at a high Level 3. Thus, we see LS's model-based explanations and justifications with respect to mechanism become more sophisticated across the year from the evaporation unit to the light unit.

Concurrently, LS's reflective talk indicated that she still continued to think about how and why phenomena happen. When asked what she wanted to figure out with these models, she replied that she "wanted to figure out how and why these things happen…how and why we see things." When asked if she had any goals for herself [in constructing and revising models], she stated, "Well, when we did evaporation and condensation with this, I didn't really know how to make models as well. *So I sort of have a goal set that I would make better explanations for how and why things happen, so I tried to add that into my model as much as I could.*" Soon thereafter, she continued with "If you don't know the how and why, you can't really explain other situations…" which shows her emphasis on the generality of the mechanism.

We interviewed LS during the first unit on chemistry in sixth grade to determine how her EIPs might have changed with a different teacher and new unit. Interestingly, we saw evidence of similar themes in her responses to those from the prior year. For example, we continued to see her emphasis on addressing the "how and why" questions in the pre-chemistry interview. For example, when questioned about why she was asked to draw the model, she recalled the models she had drawn in fifth grade and noted that a model "…helps you know how and why things happen." When asked what she wanted her model to show, LS responded that she "wanted it to show how it happens … because [the teacher] never told us to do a how and why."

In addition to the continued focus by LS from the previous to the present year on addressing the "how and why" questions during the pre-chemistry interview, LS also demonstrated her knowledge of how her model could help her learn. LS said, "…especially when we do more and more because you know more about things and then you can look back at your older models and see if you missed anything. Or when you're revising it, you can look back at your old ones." Similar to the pre-chemistry interview, LS demonstrated her continued focus on explaining "how and why" in the mid-chemistry interview.

In LS's final interview after the end of the chemistry unit, she explained how and why someone could smell an odor by giving a fully-mechanistic (Level 3) "how and why" response. She explained that how the air molecules "are just moving around and once the smell goes, the odor molecules, after they evaporate from the object, they travel around the air together and they will eventually get to your nose. That's why they're moving around all different directions." See Figure 3 for LS's corresponding model. Later in the interview, she added, "If it's more of a hot room they have more energy and they spread out and move faster. If it was a cold room I think they have less energy and they don't move as fast."

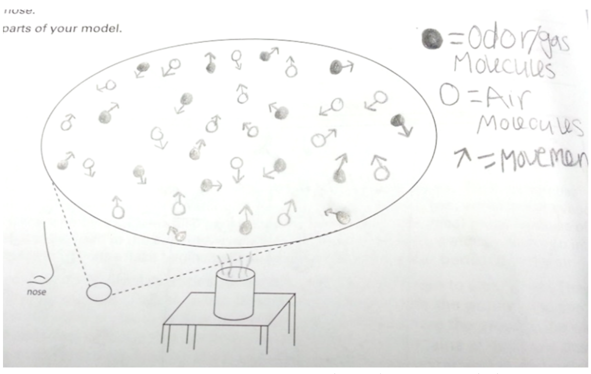

Figure 3. LS's Post Chemistry Model

In summary, we saw LS shift her level of talk and performances, as related to the EIP mechanism consideration, throughout her fifth and into her sixth grade science classes. Her first interview in fifth grade indicated that she foregrounded descriptive and detailed accounts of evaporation (and condensation, to some degree). Over time, we saw LS shift to the idea that models and their explanations should address how and why phenomena occur through her development of models and explanations that provided more mechanistic accounts in the light and chemistry units. In these units, she included non-visible components of the phenomena and described explanatory processes that captured the causal mechanisms involved. As she stated several times in her interview, LS's notions about what counts as an explanation or model (to address "how" and "why") may have guided her in seeking those causal or mechanistic aspects for her models and explanations.

Case 2: JS – Detailed Mechanisms and Evidence to Justify Explanations

JS is a student from the 2012-2013 fifth grade cohort. At the beginning of the year, JS began her pre-evaporation interview with a few ideas about how and why evaporation occurs. When asked what question she could answer with her model, she responded, "I wanted to explain evaporation. I think [the model] could use a little bit more, but I'm not sure exactly what to add yet." When describing her model, she stated, "I drew the lines [in my model] to show like air and it's supposed to show how contact with the air over time makes the water evaporate. I'm not sure exactly how that works." JS stated what she knew about evaporation (by describing that contact with the air makes it happen) but mentioned that she was not sure how it worked. This response was scored a Level 2 for mechanism because she provided a descriptive account with a non-visible component, but did not provide a theory (even if incorrect) to explain why this happened (such as the movement of water into the air).

At the end of the evaporation and condensation unit, we see evidence that JS began to develop a robust sense for mechanism and the importance of empirical evidence. In particular, she seemed to acquire the idea that a convincing causal account for the interactions of components was of paramount importance. JS showed this in a number of ways. First, when asked what question she was trying to answer with her model, she replied, "Well, basically I was trying to answer how and why condensation happens and how it works." Her response illustrates how she was already potentially attuned to mechanism in her language. More detail about what she meant came later in the interview when she asked other questions such as if the various criteria in her model were important: JS responded, "Yeah, they're definitely all important … for mechanism - what's the point of a model if it doesn't explain how it's happening? That's the whole point of it. And evidence [information] sort of shows people that it is possible." She continued on by adding, "For evaporation [the teacher] said that [the water particles] are sort of attracted to the air molecules, but *she didn't say exactly how that worked or anything*." From her response to this question and others, JS seemed to use the term "evidence" to mean "proof" or "information" in the form of a detailed causal mechanism for how the phenomenon occurs. When she was then asked if she though that she had evidence in her model, she replied, "As much as I know. [My model] says that [the water particles] slow down *but it doesn't say why they slow down. [Our teacher] never told us why they slow down, besides that they're getting near something cold.* …it's kind of hard to come by because at this grade they give you some evidence [information] but they don't tell you the whole thing." When asked how she would convince someone that her model was correct, she stated, "Well, I wanted to convince them this is how it happens, but like I said, you need evidence [information]. And I didn't get a lot of evidence [information]. I knew that it happened because I saw it in experiments, but I wasn't sure exactly how it worked…"

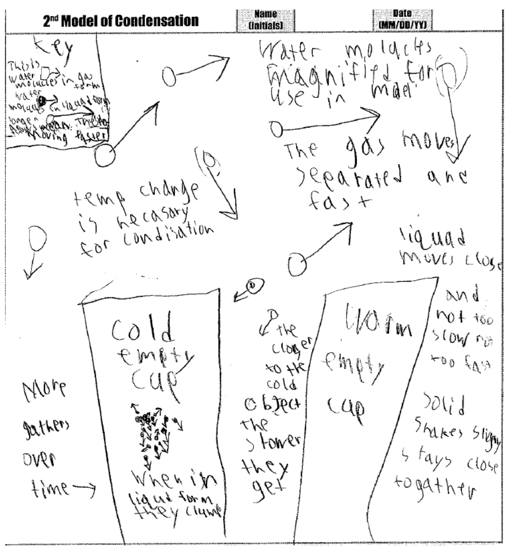

Figure 4. JS's Final Model of Condensation

Overall, her responses indicated that JS prioritized details and accuracy for how condensation occurs. From her model (seen in Figure 4) and in her talk, with respect to condensation, JS described how condensation occurred "as [the particles of water vapor] slow down, they stuck together because they're getting close and closer because they're all slowing down." JS also added that the phenomenon made her think "…[about] the ice pack… I thought that the humidity would go up [around the condensing ice pack] because I thought that the ice from it would end up evaporating. But when [the humidity level] went down, it made me realize that [the ice pack is] pulling the moisture out of the air. Even if there's more water there, if it's cold it's not going to be as much moisture in the air." In summary, JS seemed inclined towards focusing on the detailed causal accounts of condensation, consistent with a Level 3 mechanism score. Her tendency to refine her ideas seemed to focus on comparing alternative ideas to the empirical data collected in class.

When JS started the mini light unit at the end of the year, she began with the same analytical stance on mechanism and evidence that we noted in the evaporation and condensation unit. In other words, JS seemed to use her EIP related to mechanism - her sense for what an explanation involves - as a lens to orient her to the new subject matter. For example, when asked how her model explains how people see, she replied, "The human's eyes can see because they've got some light source. I'm not sure if the light source actually bounces off this or it's just somewhere from some that might have bounced off that and then bounced off a wall or something. But it's a pretty safe guess to say it bounced off this. So once light gets to the eye, the eye – I'm not sure quite how – uses the light to get an image that the brain then processes." While she was not sure exactly how the light entered the eye from the light source, she was willing to think about possible mechanisms and possibilities for how that could have happened (e.g., the light source bounced and eventually gets to an eye to create an image that the brain processes.)

Based on her extensive ideas about how and why light travels, JS seemed to have a fully-developed version of a light model by the end of the unit. Not only did she gain content knowledge about the nature of the mechanism, but she also sought and advanced her ideas about mechanism across contexts. When asked if she could explain what was happening in the model, JS talked about how the light source emits light such that "most of the light gets over here, but some of it hits some bump or groove or something and bounces into a shadow…. And then the light that hit the wall and the little bit of light that hit the shadow bounces back and some of the light that bounces back will hit the eyes to let us see." This excerpt illustrates a causal account for light scattering and reflecting using ideas such as light hitting groves and bouncing back and forth following a pathway. JS seemed to reflect more generally about transferring her analytical stance in explaining phenomena when she said, "If you're actually thinking about the way the world works, you can't look at something and not think of it like you think of everything else." Overall, JS appeared to have developed some ways of thinking about how phenomena occur (using detailed mechanistic explanations of phenomena) that may be carrying forward across contexts.

In summary, we saw JS advance her model-based explanations and reflective talk related to the EIP mechanism consideration throughout the two modeling units in fifth grade. Her first interview highlighted her concern that there was much to understand about the world that she did not know about. In her second interview, JS began to blur the boundaries between mechanism and evidence by her attempts to provide a convincing explanation for how and why something happens. By the end of the year, we saw JS consistently using a highly analytical approach in trying to understand mechanisms of how phenomena occur, even at the beginning of new units, using evidence she thought was convincing. Her notions about having a convincing and detailed model-based explanation may have guided her to seek those causal or mechanistic aspects to make sure they were consistent with empirical evidence in order to address alternative arguments.

Discussion and Implications

While there has been skepticism as to whether students can build their epistemologies in practices across conceptual contexts, our analysis of data from LS and JS indicates that some students can make significant progress constructing more mechanistic explanations of phenomena over time and across subject matter contexts as they considered the kind of model-based explanations they sought to generate. We found that LS focused on creating models and explanations that addressed how and why phenomena occurred. This pathway is consistent with her framing of the "explanation as simple causation" (Braaten & Windschitl, 2011) in which the goal and purpose of the model-based explanation is to provide a causal account of the phenomena. We found that JS focused on creating model-based explanations that were consistent with the phenomena and addressed the "why" question in a highly detailed manner. This pathway is consistent with her framing of "explanation as justification" (Braaten & Windschitl, 2011) in which the goal of the explanation is to justify the causal account with detailed mechanisms and evidence. Both cases illustrate that while the students experienced similar instructional approaches by the same teacher, the students used different pathways to develop their epistemologies in practice by leveraging different resources to frame their endeavors and to advance their work. The students' reflective language indicates that their individual framing about what counts as a model-based explanation may have foregrounded approaches that led them on their unique pathways across subject areas.

There are several important implications of this work. First, this research begins to elaborate possible pathways of students' developing practices by illustrating the importance of framing goals for explanation that can impact how students navigate their practices and develop strategies and approaches. This is important for better supporting students over time through curriculum and instruction. Curriculum can be designed to help teachers recognize and attend to student and scientific goals of the knowledge products as well as how to make those goals explicit for aligning classroom work with those goals. Understanding pathways can also help teachers identify and support EIP development for particular students. Additionally, this research deepens our understanding of how and why scientific practices bridge across contexts in productive ways. Our results show that learners can leverage and carry epistemological considerations of practice across content areas through heuristics and approaches, and potentially use them productively in those new areas. Our case studies indicate that these heuristics and approaches may be due in part to the students' foregrounding of particular epistemologies in practice and by their framing of the endeavor.

We return to our argument that engaging students in scientific practice is not adequate for scientific literacy. Students also need support in attending to epistemological considerations across curricular and instructional contexts in order to make practice meaningful and productive. As such, we advocate that EIPs should be considered through the thoughtful design of curriculum materials and instruction that align with discussions in which classrooms address questions such as, "Why are we doing what we're doing? What's our goal? How will we know whether we've gotten there?"

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